University of Cyprus

DEPARTMENT OF ARCHITECTURE

# CLIMATE CHANGE RESILIENCE OF EDUCATIONAL PREMISES IN CYPRUS:

## AN EXAMINATION OF RETROFIT APPROACHES AND THEIR IMPLICATIONS ON INDOOR COMFORT CONDITIONS AND ENERGY PERFORMANCE

**DOCTOR OF PHILOSOPHY DISSERTATION**

**CHRYSO HERACLEOUS**

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**DEPARTMENT OF ARCHITECTURE**

# CLIMATE CHANGE RESILIENCE OF EDUCATIONAL PREMISES IN CYPRUS:

## AN EXAMINATION OF RETROFIT APPROACHES AND THEIR IMPLICATIONS ON INDOOR COMFORT CONDITIONS AND ENERGY PERFORMANCE


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**A Dissertation Submitted to the University of Cyprus in Partial Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

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# Validation Page

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Dissertation Title: **Climate Change Resilience of Educational Premises in Cyprus: An Examination of Retrofit Approaches and Their Implications on Indoor Comfort Conditions and Energy Performance**

*The present Doctoral Dissertation was submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy at the **Department of Architecture** and was approved on the .................................... by the members of the **Examination Committee.***

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# Declaration of Doctoral Candidate

The present doctoral dissertation was submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy of the University of Cyprus. It is a product of original work of my own, unless otherwise mentioned through references, notes, or any other statements.

**Chryso Heracleous**

# Abstract in Greek

Η ευαισθητοποίηση σχετικά με την κλιματική αλλαγή και η επιτακτική ανάγκη μείωσης των εκπομπών διοξειδίου του άνθρακα στα κτίρια, σε συνδυασμό με τις ανησυχίες σχετικά με την άνεση των χρηστών εντός των κτιρίων λόγω της αύξησης της θερμοκρασίας όλο και αυξάνονται. Οι επιβλαβείς επιπτώσεις στην υγεία που οφείλονται στην αλλαγή του κλίματος σχετίζονται με την αύξηση της υπερθέρμανσης, τα ακραία καιρικά φαινόμενα και την κακή ποιότητα του αέρα. Έχει καταστεί προφανές ότι η Νότια Ευρώπη θα αντιμετωπίσει πιο δυσμενείς επιπτώσεις στην κλιματική αλλαγή σε σύγκριση με άλλες ευρωπαϊκές περιοχές. Η μελέτη στοχεύει στη διερεύνηση της ευπάθειας των εκπαιδευτικών κτιρίων της Κύπρου ενόψει των τρεχουσών και μελλοντικών κλιματολογικών συνθηκών μέσω έρευνας πεδίου, χρήσης ερωτηματολογίων και λογισμικού δυναμικής προσομοίωσης και, στην παρουσίαση μιας μεθοδολογίας για την αξιολόγηση της θερμικής άνεσης, του κινδύνου υπερθέρμανσης, της ποιότητας του αέρα, της οπτικής άνεσης και των επιπτώσεων που μπορεί να έχουν στην ενεργειακή απόδοση. Ο απώτερος στόχος της παρούσας διατριβής είναι να αναπτύξει μια μεθοδολογία για τη στήριξη της λήψης αποφάσεων για τη βιώσιμη προσαρμογή των υπαρχόντων εκπαιδευτικών κτιρίων μέσω μιας ολιστικής προσέγγισης παρεμβάσεων που συνοδεύεται από τεχνοοικονομική ανάλυση.

# Abstract in English

The awareness about climate change and the urgent need to decrease carbon emissions in buildings, in combination with concerns about occupants' comfort due to the rise of temperature, are continuously increasing. Harmful health impacts resulting from climate change are related to increasing heat stress, extreme weather conditions, and poor air quality. It has become evident that Southern Europe will experience more adverse effects of climate change compared to other European regions. The study aims to investigate the vulnerability of educational buildings in Cyprus, in view of current and future climatic conditions by means of field measurements, questionnaires and dynamic simulation software and, to present a methodology for the assessment of thermal comfort, overheating risks, air quality, visual comfort and their implication in energy performance. Ultimately, this study develops and proposes a methodology to support decision-making processes for the sustainable adaptation of existing educational buildings, through holistic-approach interventions, accompanied by techno-economic analysis.

Keywords: Climate change, Educational buildings in Cyprus, Retrofit approaches, Thermal comfort, Air quality, Visual comfort, Energy performance, Life cycle costing analysis.

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# Abbreviation and Symbols

| | |
|---|---|
| **IPCC** | Intergovernmental Panel on Climate Change |
| **RCPs** | Representative Concentration Pathways |
| **EPBD** | Energy Performance of Buildings Directive |
| **EPC** | Energy Performance Certificate |
| **IEQ** | Indoor Environmental Quality |
| **LCCA** | Life Cycle Costing Analysis |
| **LCC** | Life Cycle Costing |
| **EU** | European Union |
| **BPIE** | Buildings Performance Institute Europe |
| **EED** | Energy Efficiency Directive |
| **NECPs** | National Energy & Climate Plans |
| **CEN** | European Committee for Standardization (Comité européen de normalisation) |
| **MYEAK** | Energy Efficiency Calculation Methodology for Buildings |
| **ASHRAE** | American Society of Heating, Refrigerating, and Air-Conditioning Engineers |
| **RH** | Relative Humidity, % |
| **AH** | Absolute Humidity or Moisture Content, g/kg |
| **p** | Vapour Pressure, kPa |
| **MET** | Metabolic rate |
| **PMV** | Predicted Mean Vote |
| **H** | Internal heat generation in the human body |
| $E_d$ | Heat loss by water vapour diffusion through the skin |
| $E_{sw}$ | Heat loss by evaporation of sweat from the surface of the skin |
| $E_{re}$ | Latent respiration heat loss |
| **B** | Dry respiration heat loss |
| **K** | Heat transfer from the skin to the outer surface of the clothed body |
| **R** | Heat loss by radiation from the outer surface of the clothed body |
| **C** | Heat loss by convection from the outer surface of the clothed body |
| **M** | Metabolic rate |
| **L** | Thermal load |
| **PPD** | Predicted Percentage of Dissatisfied |
| **W** | Mechanical work |
| $f_{cl}$ | Clothing surface area factor |
| $t_a$ | Air temperature |
| $t_r$ | Mean radiant temperature |
| $p_a$ | Water vapour partial pressure |
| $h_c$ | Convective heat transfer coefficient |
| $t_{cl}$ | Clothing surface temperature |
| $I_{cl}$ | Clothing insulation |
| $v_{ar}$ | Relative air velocity |
| **BRE** | Building Research Establishment |
| $T_{op}$ | Operative temperature |
| **ET** | Effective temperature |
| **SCATS** | Sound change and the acquisition of timing in speech |
| **DR** | Draft rate |
| **PD** | Percentage of Dissatisfied due to local discomfort |
| **HVAC** | Heating, ventilation, and air conditioning |
| $T_c$ | Optimal operative temperature for comfort/ Neutral temperature |
| $T_{pma(out)}$ | Prevailing mean outdoor temperature |
| **SCATs** | Smart Controls and Thermal Comfort |
| **AMV** | Actual Mean Vote |
| **Trm** | Running mean temperature |
| $CO_2$ | Carbon Dioxide |

| | |
|---|---|
| **CO** | Carbon Monoxide |
| **aPMV** | adaptive PMV |
| **cPMV** | corrected PMV |
| **Epmv** | extended PMV |
| **RTC** | Rational Thermal Comfort |
| **ATC** | Adaptive Thermal Comfort |
| **TMY** | Typical Meteorological Year |
| **IAQ** | Indoor Air Quality |
| **VOCs** | volatile organic compounds |
| **PM** | Particulate Matter |
| **$SO_2$** | Sulfur dioxide |
| **ppm** | parts per million |
| **EPA** | United States Environmental Protection Agency |
| **NAAQS** | National Ambient Air Quality Standards |
| **WHO** | World Health Organization |
| **CAFE** | Clean Air for Europe |
| **REHVA** | Representatives of European Heating and Ventilation Associations |
| **ODA** | outdoor air |
| **Pb** | Nitrogen Dioxide |
| **$O_3$** | Ozone |
| **ACH** | Air Changes per Hour |
| **SBS** | Sick Building Syndrome |
| **IARC** | International Agency for Research on Cancer |
| **MVHR** | Mechanical Ventilation Heat Recovery |
| **SAD** | Seasonal Affective Disorder |
| **IEA** | International Energy Agency |
| **IESNA** | Illuminating Engineering Society of North America |
| **CIE** | International Commission on Illumination |
| **DF** | Daylight Factor |
| **DA** | Daylight Autonomy |
| **UDI** | Useful Daylight Illuminances |
| **DAmax** | Maximum Daylight Autonomy |
| **DGP** | Discomfort Glare Probability |
| **Ev** | Vertical eye illuminance |
| **CIBSE** | Chartered Institution of Building Services Engineers |
| **BBR** | Boverket´s building regulations- Swedish Building Code |
| **UEA** | University of East Anglia |
| **NPV** | Net Present Value |
| **PV** | Present Value |
| **FV** | Future value |
| **i** | Discount rate |
| **n** | Time period |
| **$C_o$** | Initial investment costs |
| **$C_n$** | Cash flow in period |
| **Cg** | Global cost over the calculation period |
| **$C_I$** | Initial investment costs for the energy efficiency measure or set of measures j |
| **$C_{a,i}$ (j)** | Annual cost during the year I for measure or set of measures j (including running costs and replacement costs) |
| **$C_{c,I}$ (j)** | Annual cost of greenhouse gas emissions |
| **$V_{f,\tau}$ (j)** | Residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year) |
| **$R_d$ (i)** | Discount factor of year |
| **$R_r$** | Interest rate |
| **BMI** | Building Maintenance Information |
| **TRNSYS** | Transient System Simulation Tool |

| | |
|---|---|
| **KGCC** | Koppen-Geiger Climate Classification |
| **UCY** | University of Cyprus |
| **OUC** | Open University of Cyprus |
| **CUT** | Cyprus University of Technology |
| **ATI** | Higher Technological Institute |
| **ASC** | Adaptive Comfort Standards |
| $V_r$ | Relative air speed |
| $t_g$ | Globe temperature |
| $V_a$ | Air velocity |
| **D** | Globe diameter |
| **ε** | Emissivity |
| **TDR** | Temperature Difference Ratio |
| $T_{max\_out}$ | Maximum outdoor air temperature |
| $T_{max\_in}$ | Maximum indoor temperature |
| $T_{fluctuation\_out}$ | Fluctuation of the outdoor temperature |
| $T_{min\_out}$ | Minimum outdoor air temperature |
| **CDH** | Cooling degree-hours |
| **HDH** | Heating degree-hours |
| $T_{o\_average}$ | Average hourly operative temperature |
| $T_{lower\_limit}$ | Lower acceptability limit of comfort temperature |
| $T_{upper\_limit}$ | Upper acceptability limit of comfort temperature |
| **KKEA** | Centre for Educational Research and Evaluation |
| **TS** | Thermal Sensation |
| **TP** | Thermal Preference |
| **TA** | Thermal Acceptability |
| **AM** | Air Movement Preference |
| **IES-VE** | Integrated Environmental Solutions Limited Virtual Environment |
| **R** | Thermal Resistance |
| **ρ** | Density |
| **λ** | Thermal conductivity |
| **d** | Thickness |
| **U-Value** | Thermal transmittance |
| **Cp** | Specific heat capacity |
| **Rsi** | Internal surface thermal resistance |
| **Rse** | External surface thermal resistance |
| **RMSE** | Root Mean Square Error |
| **MAE** | Mean Absolute e=Error |
| **MAESD** | Standard Deviation of MAE |
| **We** | Weighted exceedance |
| **Tmax** | Maximum acceptable temperature |
| **Tupp** | Upper limit temperature |
| **Mc** | maintenance cost including operation, inspection, cleaning, adjustments, repairs and consumable items |
| **BREEAM** | Sustainability assessment method for masterplanning projects, infrastructure and buildings |
| **Ev** | Vertical eye illuminance |
| **LS** | Luminance of the source |
| **ωs** | Solid angle of the source seen by an observer |
| **P** | Position index, which expresses the change in experienced discomfort glare relative to the angular displacement of the source (azimuth and elevation) from the observer's line of sight. |

# List of Publications

Book Authorship

1. Philokyprou, M., Michael, A., Thravalou S., Heracleous C., **The Bioclimatic Aspects of the Vernacular Architecture of Cyprus**, ISBN: 978-9963-33-9912-4-2, Nicosia, December 2014, in Greek.

Greek Journal Articles

1. Philokyprou, M., Michael, A., Thravalou S., Heracleous C., **Sustainability and Architectural Design: The case of traditional architecture of the Historical Centre of Nicosia**, Annual Review of History, Society and Politics, Promitheas Research Institute, Nicosia, Volume 6, 2020, ISSN 2421-7700, in Greek.

Refereed International Scientific Journal Articles

- Heracleous C., Michael A, Savvides A., Hayles C., **Climate change resilience of schools in Cyprus: An examination of retrofit approaches and their implications on thermal and energy performance**, approved in the Journal of Building Engineering (second-round revision).

1. Heracleous C., Michael A., **Thermal comfort models and perception of users in free-running school buildings of East-Mediterranean region**, Energy and Buildings, 215, 109912, 2020. DOI: https://doi.org/10.1016/j.enbuild.2020.109912

2. Heracleous C., Michael A, **Experimental assessment of the impact of natural ventilation on indoor air quality and thermal comfort conditions of educational buildings in the Eastern Mediterranean region during the heating period,** Journal of Building Engineering, 26, 100917, 2019. DOI: https://doi.org/10.1016/j.jobe.2019.100917

3. Heracleous C., Michael A, **Assessment of overheating risk and the impact of natural ventilation in educational buildings of Southern Europe under current and future climatic conditions**, Energy 165 (Part B): 1228-1239, 2018. https://doi.org/10.1016/j.energy.2018.10.051

4. Michael A., Heracleous C., **Assessment of natural lighting performance and visual comfort of educational architecture in Southern Europe: The case of typical educational school premises in Cyprus,** Energy and Buildings, 140: 443-457, 2017. https://doi.org/10.1016/j.enbuild.2016.12.087

5. Michael A., Heracleous C., Thravalou S. Philokyprou M., **Lighting performance of urban vernacular architecture in the East-Mediterranean area: Field study and simulation analysis**, Indoor and Built Environment, 26/4 (2017) 471-487, SAGE, First Published Online: December 10, 2015, DOI: 10.1177/1420326X15621613.

Refereed International Conference Proceedings Papers - Full Papers

1. Heracleous C., Michael A., Charalambous C., Efthymiou V., **Evaluation of thermal comfort and energy performance of a case study in vernacular architecture of Cyprus**, 35th PLEA Conference of Sustainable Architecture and Urban Design, Planning Post Carbon Cities, A Coruña, 1st-3rd September 2020.

2. Heracleous C., Michael A, Savvides A., Hayles C., **Passive measures for improving thermal comfort and energy performance of educational buildings in Cyprus**, SEEP

2019 – 12th International Conference on Sustainable Energy & Environmental Protection, United Arab Emirates- University of Sharjah, 18th- 21st November 2019, pp. 123-128, ISBN: 978-9948-36-625-6.

3. Heracleous C., Michael A, **Experimental assessment of thermal comfort conditions in educational buildings in Cyprus using different ventilation strategies and window opening patterns**, CATE conference 2019 – Comfort at the Extremes: Energy, Economy and Climate, Dubai, 10-11 April 2019, pp.636- 649.

4. Heracleous C, Charalambous C., Michael A., Yiannaka A., Efthymiou V., **Development of an innovative compact hybrid electrical-thermal storage system for historic building integrated applications in the Mediterranean climate**, CATE conference 2019 – Comfort at the Extremes: Energy, Economy and Climate, Dubai, 10-11 April 2019, pp.364-376.

5. Savvides A., Michael A., Vassiliades C., Kartsiou A., Heracleous C., Xenophontos M., Ierides V., Gianni N., Maimaris C, **Energy efficient prefabricated housing units: Product review and the development of a Cypriot paradigm**, In: International Conference on Sustainable Design of the Built Environment, SDBE London, UK, 12-13 Sept. 2018, pp.388-397.

6. Heracleous C., Michael A., **Thermal comfort conditions and air quality in educational buildings in Cyprus during the heating period: the impact of natural ventilation**, In: Second International Conference on Sustainable Design of the Built Environment, SDBE London, UK, 12-13 Sept. 2018, pp.1108-1119.

7. Heracleous C., Michael A., **Climate Change and Thermal Comfort in Educational Buildings of Southern Europe: The case of Cyprus**, In: 10th International Conference on Sustainable Energy and Environmental Protection, Bled, Slovenia, 27-30 June 2017, pp.183-193, ISBN 978-961-286-050-9.

8. Heracleous C., Ioannou I., Philokyprou M. and Michael A., **Hydrothermal Performance of a Stone Masonry Wall in a Traditional Building in Cyprus**, In: International PLEA Conference, Architecture in (R) Evolution, Edinburgh, UK, 3-5 July 2017, volume III, pp.5030-5037, ISBN 978-0-9928957-5-4.

9. Heracleous. C, Lo S., **Technical Viability of Low-Energy Strategies to meet Passivhaus Standards for Domestic Buildings in Cyprus**. In: 31st International PLEA Conference, Architecture in (R) Evolution, Bologna, Italy, 9- 11 September 2015, paper no. 46, Bologna: Building Green Futures.

10. Michael A., Heracleous C., Malaktou E., Savvides A., Philokyprou M., **Lighting Performance in Rural Vernacular Architecture in Cyprus: Field Studies and Simulation Analysis.** In: 31st International **PLEA Conference**, Architecture in (R) Evolution, Bologna, Italy, 9- 11 September 2015, paper no. 304, Bologna: Building Green Futures.

# Chapter 1. Introduction

## 1.1. Preface

The scope of this thesis is part of the broader problem of ensuring appropriate living conditions in buildings, in present and future climatic conditions and is directly related to the theoretical background developed by the architectural and environmental design field. In modern societies, people spend over 90% of their time indoors [1]. With the exception of their home, students spend more time in educational buildings than in any other place, highlighting the importance of providing comfortable indoor thermal conditions in these buildings.

It has already become evident that climate change will eventually lead to increasingly hot days that will significantly affect the indoor comfort conditions and energy performance of buildings [2]. The need for providing acceptable comfortable conditions arises from the peculiarities of the operation of school buildings. School buildings are considered an important building type in relation to the effects of indoor conditions on students' health, learning and performance. School comfort conditions are related to thermal and visual comfort as well as air quality. The improvement of the energy performance of educational buildings refers to a series of adaptation measures and strategies related to the construction and operation of the building that aim to improve the performance, reduce the energy consumption of the building and reduce the environmental impacts. This study aims to enhance decision-making processes in such issues relating to the effects of climate change by providing to policy-makers and other interested parties valuable insight regarding the possible negative effects caused by climate change, as well as the available adaptation options for slowing down these effects.

The proposed improvements will provide knowledge relevant to the exploitation of basic principles of sustainable design while increasing environmental awareness amongst students and society in general, as schools comprise the most promising public building types to act as lighthouse projects. Students can experience the tangible improvements to the building envelope of classrooms and they can learn how to support energy saving and indoor comfort conditions through responsible user behaviour.

## 1.2. Background of the research

The **building sector** contributes up to 30% of the global annual greenhouse gas emissions and consumes up to 40% of all energy [3]. The consequences of the global greenhouse effect are global warming and extreme weather phenomena. Climate change is taking place and is affecting cities, including both their built environment as well as their residents- especially their most vulnerable ones. The relationship between the severity of the impacts of climate change and the frequency of climatic extreme phenomena is highlighted in several studies [4]–[10]. A growing number of cities in Europe have taken initiatives to modify their energy production, their consumption patterns and greenhouse gas emissions in order to develop adaptation policies to climate change, including specific policies for the built environment in particular [11].

It is understood that in order for a society to become **resilient to climate-change** it must have an infrastructure that is both fully functional and sustainable. Much of the built environment is aging, carbon intensive, and not fit for purpose. At present, there are two opportunities to build sustainable, climate resilient infrastructure: **new buildings** and reconstruction following for example extreme weather events. In all other instances, **buildings must be retrofitted**, if they are to be future-proofed for predicted changes in climate. Upgrading existing buildings is a crucial but neglected issue in the context of sustainable architecture as most studies focus on new buildings. However, there are many reasons to demonstrate the vital importance of upgrading existing buildings to achieve the goal.

**Discomfort conditions** and high demand for heating energy in winter and overheating in summer are important issues in the building sector and the effects of climate change on these parameters is maximized. Given that a building's life cycle is over 50 years and that a holistic replacement of the existing building stock would take over 100 years, at great economic and environmental cost, **upgrading** is considered very important in reducing energy consumption and $CO_2$ emissions [12]. Replacing the existing building stock has almost always greater harmful environmental impacts than upgrading due to demolition, waste management and the replacement of higher carbon materials. The results of retrofitting a building and its reuse may seem small when considering a single building; however, the absolute carbon-related impact reduction can be substantial when these results are scaled across the building stock of a city. Based on a study undertaken by the National Trust for Historic Preservation, retrofitting is particularly important for countries which are dependent on fossil fuels and more extreme climate fluctuations drive higher energy use. Additionally, upgrading is a tool that extends the lifecycle of buildings with architectural and historical value. It is noteworthy that 38% of Europe's building stock was constructed before 1960 and 45% between 1961-1990 [13] and according to statistics, 70% of the current existing building stock is likely to be still in use in 2050 [14]. Therefore the potential positive impact of upgrading is greater than building new constructions as their contribution to the portion of highly efficient buildings is smaller. In order to limit the rise of the global average temperature, a significant increase of the rate and depth of existing building energy efficiency renovations is required [15].

It has become evident that specifically **Southern Europe** will experience more adverse climate change effects compared to other European regions. Cyprus is projected to face significant temperature increases and a decline in rainfall levels. Specifically, estimations for the period of 2020 to 2050 show an increase in hot summer days with maximum temperatures exceeding 38°C for an additional two weeks per year compared to the current situation. Additionally, the frequency of warm nights with minimum temperatures above 25°C will increase for an additional one month compared to current conditions [16]. According to the last report of the IPCC [6], the best case scenario (RCP

2.6) projects an increase in average surface temperature of about 1.5°C, while the worst case scenario (RCP 8.5) projects an increase of about 3-4°C by the end of the century.

The residential and services sector collectively remain the second largest energy consuming sector in Cyprus (after transport) presenting a significant energy saving potential [17]. **The first mandatory energy performance requirements** in building codes in Cyprus were introduced with the adoption of the 2007 Decree on the Minimum Energy Performance Requirements for Buildings (Decree 568/2007). The 2007 Decree, which was adopted as a result of the implementation of the EU's Energy Performance of Buildings Directive (EPBD), introduced prescriptive requirements expressed as minimum heat transfer coefficients for the building envelope for all new buildings. The same prescriptive requirements also applied to buildings over 1000m$^2$ undergoing major renovation. The minimum requirements were revised in 2009 and performance-based requirements in the form of minimum energy class B under the Cypriot EPC system [18]. Statistical data published by the Cyprus Energy Agency show that that less than 10% of the residential building stock are equipped with wall, roof or basement insulation, while over 50% of the buildings remain without any insulation. Like residential buildings, the rest of the buildings when they were erected were not required to apply thermal insulation or any other energy saving measures. Approaches to the building envelope were the same for all categories of buildings [19].

**Educational buildings** comprise a significant portion of the public non-residential building stock. The majority of school buildings in Cyprus were designed and erected by the Technical Services of the Cyprus Ministry of Education and Culture. This renders the designs uniform in terms of their construction, morphology and typology. Therefore, the architectural design of schools features considerable similarities; it is substantially standardized in terms of building material and methods of construction. A large number of typical school buildings were erected in the years that followed the Turkish invasion of 1974 to satisfy the building needs presented. As a result of that development, educational buildings are characterized by poor energy performance. Energy saving measures were only introduced very recently (2007) and are therefore characterized as less –energy efficient compared to other public buildings. Recently, a special committee has been set up by the Ministry of Education to exchange views on the installation of air conditioning units in school classrooms [20]. The emerging problem is not related to the installation of air conditioning systems in the classrooms, but rather the worsening of comfort and well-being in public school classrooms during the late spring and early autumn days due to the high sunshine and high concentration of people in them which in turn lead to poor indoor air quality.

School buildings are considered an important building type in relation to the effects of indoor conditions on **students' health, learning and performance** [21]. In addition, classroom conditions can also affect teaching quality which correlates with the overall learning process of the students [22]. Indoor environmental conditions in schools are of particular importance, as children are less resistant to adverse environmental conditions compared to adults, and thus, the magnitude of the effects of poor indoor air quality and high indoor air temperatures on school work performance is suggested to be larger than that on office work performance of adults [23], [24]. Learning performance can differ from office work performance, mainly because the former is perceived as efficiency in acquiring knowledge, while the latter is often about efficiency in using the acquired knowledge [25]. Despite the importance of maintaining both satisfactory indoor air quality and thermal comfort in schools, very few studies have investigated thermal comfort aspects within classrooms in comparison to air quality, especially regarding the effect of thermal quality on students' performance in schools which is just as important [26].

Singh et al.[27], who researched the development in **thermal comfort** studies in classrooms in the last 50 years, found that the studies on thermal comfort in educational buildings are scarce compared to the broader academic field of thermal comfort studies. Although there is a growing concern about students' performance and well-being, the gap between students' performance and indoor environmental quality is still valid. According to the study, the growing number of studies in the field increases the chances of covering the majority of issues related to thermal comfort, overcoming the limitations and giving valuable knowledge about drawing correct conclusions on the best way to design or give feedback related to buildings designed for teaching and learning, to behaviour, clothing and furnishing infrastructure in classroom practices.

Furthermore, another vital aspect to be considered in school design is **daylighting**. Numerous studies have shown the positive and negative influence of daylight on health and performance of students and teachers. The benefits reported from daylighting strategies include increased student sociability and concentration [28], less stressful environment for students [29], improved academic performance [30], [31] and also reduced energy cost [32]. It is evident that the visual comfort of school buildings should be carefully considered by architects. Thermal or visual comfort and energy consumption sometimes conflict each other. Therefore, it is necessary to assess all the parameters in order to find the optimum and balanced solution [33].

According to the new **Climate and Energy Policy Framework -** National Governance System - National Action Plan 2021-2030, the objective is to implement important interventions in the residential and tertiary sector that will aim at penetrating more efficient electrical appliances and improving energy efficiency of buildings. Specifically, the decisions of the European Council regarding the 2021-2030 Action Plan are based on three objectives at EU level, i.e. (a) at least a 40% reduction in greenhouse gases from 1990 levels, (b) at least 32.5% improvement in energy efficiency, (c) at least 32% share for renewable energy [34].

Additionally, throughout the Recast **Energy Performance of Buildings Directive** (EPBD) it is requested that "the public sector in each Member State should lead the way in the field of energy performance of buildings" and "buildings occupied by public authorities and buildings frequently visited by the public should set an example" [35]. Among the most promising public building types to act as lighthouse projects are school buildings. Pupils can experience the visible improvements to the building envelope of classrooms and they can learn how to support energy savings by responsible user behaviour.

The potential and significance associated with the retrofitting of the Cypriot educational building sector are getting higher when considering the future population growth. Based on some statistics regarding Cyprus Population Forecasts, the growth is slow and by 2050 the percentage of change is reduced year in year out and starts to be negative from 2065 to 2090 [36]. According to statistics from Eurostat, Cyprus is projected to see its median ages rise to 52.6 by 2080 compared to the 37.2 in 2016, leading to an increase of elderly in the total population (19 percentage point). Cyprus is one of the two countries of Europe that will have a decrease of the young-age dependency ratio by 3.5 percentage points by 2080. Therefore, the need for new educational buildings to cover the educational process seems to be low and the existing building stock acquires significance. Additionally, based on the Ministry of Education, Culture, Sport and Youth, the rhythm of replacement of existing educational buildings is very slow and there is no plan for replacement of educational building stock [37].

The use of **targeted mild and passive measures** seems to solve the problem at a great extent while also improving the overall comfort and well-being in public building classrooms throughout the entire year, for the benefit of the educational community.

The factors summarized above show the challenge of establishing the most appropriate comfort conditions for educational buildings with respect to the age of children while also reducing the energy consumption of buildings in order to keep up with European Union Directives on low energy buildings, eventually reducing the effects of climate change in the future.

## 1.3. Significance and contribution of the thesis

Providing thermal comfort in classrooms is an obvious necessity because students spend up to one-third of the day in school. Indoor environmental quality (IEQ) influences students' health, attitude and performance. In combination with outdoor air pollutants, temperature is an additional important factor affecting students' performance. Elevated air temperature during the late spring and early autumn days due to the high sunshine, and poor air quality due to high concentration of people especially during winter, worsen the state of comfort in classrooms of Cyprus. The emerging problem has led to several discussions about whether the installation of air conditioning is the appropriate solution for the achievement of thermal comfort. However, this approach will lead to a number of other problems, including issues related to load, durability and suitability of indoor electrical installation systems and rising energy that is contrary to the new climate policy directives. In addition to assessing thermal behaviour and air quality, the effect of natural lighting on children's health and productivity is of great importance and should be considered in any proposed strategy. The effects of climate change will lead to more adverse effects on both comfort and energy consumption if no action is taken. This study will inform decision makers about the current conditions of thermal comfort and energy needs of educational buildings of Cyprus in a quantitative manner, a arguing for the necessity of energy retrofitting measures. On this basis, the research soughts to identify the methods and practices that will bring about a definitive and sustainable solution to the problem with respect to the anthropogenic and natural environment.

**Energy conservation** and, most importantly, **improving children's comfort and performance** in classrooms require more research in the area. The results of previous studies conducted in classrooms found that this is an area that only a limited number of studies were performed compared to the broader academic field of thermal comfort studies [27]. There is a need to overcome the limitations of thermal comfort and actual thermal perception of children by providing valuable knowledge, which will draw correct conclusions regarding the best ways to design buildings and teaching spaces based on statistical analysis.

This study is significant as it addresses in a systematic, **qualitative and quantitative manner** the performance of educational architecture through the investigation of typical school premises in Cyprus. This study takes a step forward and extends the existing research conducted in school buildings of Cyprus performed by Michael [38]. The study developed a **multi-criteria evaluation methodology** and helps **decision-making** for the upgrade and decarbonisation of existing educational building stock that takes into account comfort, energy upgrading and adaptation to climate change. The various methodological approaches, i.e. literature review, monitoring, experimental procedure, dynamic simulation, questionnaires and on-site observation, allow a comparison of the research results with the aim to identify possible divergences and convergences between them and ensure the validity of the outputs as much as possible.

The research adds value to the literature regarding the **correlation between the different environmental parameters** in school buildings during the entire year covering both worst case scenarios of operation of educational buildings, which is those in winter and summer. Moreover, the data were selected during both occupied and unoccupied periods in order to determine the **contribution of users** to the performance of the building.

This research also offers an **understanding of thermal comfort** conditions in naturally ventilated educational buildings and analyses whether the children's thermal comfort zone, perception and tolerance is compliant with comfort standards which are widely implemented in adult studies using a statistical analysis. The thesis provides a basis to improve evaluation methods when studying school-aged children in the field of thermal comfort.

Although many studies [39], [40] have monitored various environmental parameters in educational buildings, much fewer have investigated the interrelation between **ventilation rates or $CO_2$ levels and their health effects.** Moreover, the operation and maintenance of school facilities are often neglected leading to a persistence of environmental problems in schools; therefore, there is a need for research regarding school building construction and rehabilitation in order to plan properly and ensure sufficient conditions for users to fulfil their activities The need to improve **air quality** in educational buildings is exacerbated further by the Covid-19 pandemic, constituting the future contribution of this research even greater. This study adds value to the literature regarding the correlation between the different environmental parameters in school buildings and proposes sufficient improvements of the conditions in order to enhance students' productivity and satisfaction.

The study **highlights the importance of natural ventilation** for both thermal comfort and air quality and examines its potential in a great extent. Although natural ventilation is a well-known strategy for reducing indoor temperatures during cooling period, the present thesis aims to examine at what extent natural ventilation can improve thermal comfort conditions in the specific climate and building typology. Classrooms in educational premises of Southern Europe have diachronically employed natural ventilation as an essential cooling strategy during the summer months, but also as a strategy to rarefy the concentration of internal pollutants and achieve amelioration of indoor air quality. The effectiveness of different ventilation strategies and patterns are investigated for the achievement of the optimum conditions in both winter and summer, with various methodological approaches.

Additionally, research studies, where the emphasis is the **impact of climate change** on buildings are limited and according to the literature, there are difficulties for direct comparison of the energy consumption between the buildings, due to variations on the climatic conditions, building characteristics and building operation. Specifically, there is no other study that focuses on the impact of climate change and **overheating risk** on the thermal and energy performance of educational buildings in Cyprus. The study thus, contributes to knowledge in the field of the impact of climate change and **assesses the potential and effectiveness of adaptation measures, both during current and future climatic conditions**. The adaptation measures mostly refer to passive or mild measures that aim to reduce the negative impact of climate change minimising the energy footprints. The evaluation of the resilience of existing educational buildings is useful in understanding the necessity of energy retrofitting measures in view of future climatic conditions, by contributing to energy efficiency policies and decision-making processes regarding retrofit interventions.

In addition to assessing thermal comfort and air quality, the research considers the **natural lighting** performance and visual comfort of educational architecture, aiming at the overall assessment of comfort. The multi-criteria evaluation methodology used introduces a holistic approach to the investigation of natural lighting performance and visual comfort, and therefore contributes to knowledge in the field of daylighting. The evaluation of the daylighting performance of typical classrooms produced important and valuable findings in terms of the amount and uniformity of light and the prediction of glare. Moreover, the research moves a step forward in defining design guidelines for the improvement of daylighting performance and thus, of human visual comfort in educational buildings in Cyprus and in other areas of Southern Europe with similar climatic characteristics and typologies in educational architecture.

Considering that similar building arrangements of linear disposition of classrooms connected with semi-open corridors like the ones mentioned in this study, are commonly found in other countries of the Eastern Mediterranean region that share similar climatic conditions with Cyprus, the results of the current study can be applied in a **wider sample of buildings**.

The proposed improvements can increase **environmental awareness** as schools are among the most promising public building types to act as lighthouse projects. Classes can offer pupils first-hand experience on visible improvements to the building envelope with students learning how to support energy savings and indoor environmental quality by responsible user behaviour.

Finally, the present study presents an approach to design and assess energy demand retrofitting scenarios based on long-term cost effectiveness. The approach combines energy demand modelling and retrofit option ranking with **life-cycle costing analysis** (LCCA). These options may have very different upfront costs but also very different carbon implications and result in different life expectancy predictions. The aim is to give the stakeholders as much information as possible about their interventions, so that they can make informed decisions. This information will be used to **develop a framework** that could be used more extensively to **support decision making in retrofitting existing educational buildings for climate change resilience**.

## 1.4. Methodological approach

Given the importance of enhancing schoolwork performance and productivity in learning environments and improving the energy performance of educational buildings, the present study aims to provide a basis for introducing a better understanding of thermal and visual perception of secondary school students, and in parallel, to evaluate the indoor comfort conditions and energy performance of educational premises in Cyprus under current and future climate scenarios. Further to the above, the study aims to develop a methodology to support decision-making for the sustainable adaptation of existing buildings through a holistic approach intervention accompanied by a techno-economic analysis.

The main line of reasoning taken by the thesis is inductive. It undertakes an in-depth multi-aspect investigation of a single case study building to build a case for broader measures for schools buildings in Cyprus. The existing literature conducted in school buildings of Cyprus performed by Michael [38] gives the opportunity to generalize that 90.5% of educational buildings can be categorized as typical school buildings. The specific building stock is characterized by significant repetition of spatial configurations and design elements and is characterized by uniformity in terms of typology, morphology and construction. Moreover, this typology of buildings allow for the evaluation of thermal and energy performance in smaller study models with different orientations as classrooms appears in varied orientations without substantial concerns regarding a climatically rational design. Therefore, the present thesis takes a step forward in order to analyse in great and deep investigation a case study building that is representative school building in order to generalize the results in the entire educational building stock in Cyprus.

The investigation, analysis and documentation of the current research is carried out using three methodological approaches. Firstly, the **critical literature review** establishes the theoretical framework of the thesis. The theoretical background refers to the definition of the necessity of the research based on the literature gap, the definition of the typical and representative case study and its characteristics based on the structure, organization, form and function, the definition of predicted climate change conditions and its impact on thermal comfort and energy performance of buildings. All the above, enrich the research tools and finally formulate methodological approaches to the investigation of comfort conditions of educational buildings.

Secondly, the **scientific approach** focuses on the quantitative, objective recording of environmental and other factors that influence comfort conditions and the determination of energy performance in schools. In addition, this is achieved by experimental procedure and dynamic software simulation on comfort and energy performance parameters of the building envelope under the current and future climatic conditions.

Thirdly, the **anthropocentric approach** focuses on the qualitative recordings of the social characteristics of the school environment and introduces parameters related to biological, emotional, and psychological data that influence the subjective sense of user comfort. This is achieved through on-site observation, questionnaires and interviews, seeking to collect and evaluate data from users of the site.

The assessment of the vulnerability of educational buildings in Cyprus in view of current and future climatic conditions is carried out using multiple research tools, thus allowing for a comparison of the research results from the different methodological approaches. The results of the qualitative and quantitate approaches are compared and analysed highlighting similarities or differences between them. This process seeks to achieve a holistic approach to the research subject and to ensure the validity of the outputs as much as possible. Moreover, the research results derided from this thesis constitute useful data for the development of a methodology to support **decision-making** for the sustainable adaptation of existing buildings through a holistic approach intervention accompanied by a techno-economic analysis.

## 1.5. Research objectives of the thesis

The framework of the main research objectives facilitates a better formulation of the methodology. This research involves four fundamental phases that form the thesis structure:

1. Critical literature review to establish the theoretical framework of the thesis
    - To define the general historic and legal context regarding the energy performance of buildings

- To determine influential factors affecting comfort conditions in buildings
- To define comfort approaches and review studies in educational buildings
- To define influential factors affecting indoor air quality in educational buildings
- To identify the impact of air quality on the performance and well-being of students
- To identify the impact and significance of natural ventilation in free-running buildings
- To identify the importance of daylight on the performance of students
- To review the predictions of future climatic conditions and how these will affect both comfort and energy performance
- To identify technical solutions for the achievement of required overall comfort conditions in educational buildings
- To review the economic assessment indices

2. Develop a multi-criteria methodology to assess the overall comfort conditions and energy performance of educational buildings
    - To identify different methodological approaches for evaluation of thermal comfort
    - To identify different methodological approaches for evaluation of air quality
    - To identify different methodological approaches for evaluation of daylighting performance and visual comfort
    - To establish different methodological approaches for the evaluation of energy performance
3. Evaluation of comfort condition of educational buildings under current and future climatic conditions for the existing state and retrofitting approach
    - To identify the thermal comfort conditions under which students feel comfortable in naturally ventilated classrooms during the warm and cool periods of the school year through different methodological approaches
    - Through comfort field survey and simultaneous physical measurements of indoor and outdoor climate:
        - To characterize the physical conditions of the naturally ventilated classrooms
        - To identify the actual thermal perception of the students in the classroom
        - To derive the actual thermal sensation of students and measure the required data for the predictions of the mean thermal sensation for the comparative study
        - To understand and analyse using statistical analysis the relationship between the measured physical conditions and students' thermal sensation
        - To identify and analyse using statistical analysis whether activities, clothing, and indoor environmental control affects thermal sensation

    - To understand and analyse using statistical analysis if there is any gender difference in relation to thermal sensation and acceptable indoor operative temperature ranges
    - To examine students' thermal comfort responses and compare them with acceptability criteria specified in the EN 15251 adaptive comfort standard
    - To examine the energy performance of educational buildings
    - To examine the indoor air quality in classrooms and identify an optimum ventilation strategy for both indoor air quality and thermal comfort
    - To identify the actual perception of students for air quality in classrooms
    - To evaluate the effectiveness of natural ventilation on thermal comfort and indoor air quality
    - To characterize the natural lighting levels of classrooms
    - To identify the actual perception of students for the lighting levels in classrooms
  - Through modelling in a dynamic software simulation:
    - To identify the overheating risk of typical classrooms under both current and future climate scenarios
    - To define the energy performance of educational buildings under both current and future climate scenarios
    - To investigate the positive contribution of adaptation measures and their connection to thermal comfort and energy performance under both current and future climate scenarios
    - To normalize and rank the retrofitting scenarios and evaluate them based on the life cycle costing analysis.
    - To examine the impact of natural ventilation on thermal comfort and overheating risk
    - To understand the natural lighting performance and visual comfort of educational buildings in the existing state
    - To examine the impact of proposed improvements on natural lighting performance and visual comfort

4. Analysis of the results
    - To compare the results with the outcomes of previous studies

## 1.6. Structure of the thesis

The thesis is organized in three main sections which refer to: (i) the research background and literature review of main examined fields, i.e. energy, thermal comfort, air quality and visual comfort, (ii) the multi-criteria methodology for the assessment of comfort and energy performance of educational buildings under current and future climatic conditions and (iii) the results drawn from the research relevance to the drafting of proposals for optimizing the comfort and energy performance of buildings.

Specifically, the **first section** deals with theoretical issues and refers to legal context and reviews the existing literature about the energy performance of buildings in Europe, the legislative framework and directives for climate strategies and targets set by the EU and the Cyprus energy policy for achieving energy and environmental goals (Chapter 2). Additionally, it develops a conceptual framework and builds a theoretical basis for defining approaches to thermal comfort based on the available literature, explores the existing approaches of thermal comfort widely used in academic research, and describes the inclusion of these approaches in international and European standards (Chapter 3). Moreover, it demonstrates the basic principles of air quality and provides a context for the investigation of the relationship between the indoor environment and the air quality of educational buildings in naturally ventilated buildings (Chapter 4). The following chapters explore the basic principles of visual comfort (Chapter 5) and review the climate change observations and projections based on the literature investigating their effect on buildings (Chapter 6). Finally, this section reviews technical solutions for the achievement of required overall comfort conditions (Chapter 7) and discovers issues relevant to cost-effectiveness (Chapter 8).

The **second section** deals with the development of the methodology for the assessment of comfort and energy performance of educational buildings in Cyprus. Specifically, the analysis of the climate of Cyprus (Chapter 9) and the structure and organization of the Cypriot educational system are recorded, and the representative types of the existing educational buildings are investigated, aiming at the establishment of a methodology for the selection of the appropriate sample of school buildings (Chapter 10). Later, a multi-criteria evaluation and decision support system is developed for thermal comfort and energy performance of existing and upgraded educational buildings under current and future climatic conditions, using quantitative study through field measurements, dynamic software simulation as well as LCCA and qualitative survey through questionnaires (Chapter 11). Beyond that, a methodology to assess the indoor air quality and possible improvements in correlation with thermal comfort in educational buildings is proposed, using field measurements and observation as well as qualitative survey through questionnaires. (Chapter 12). Additionally, a multi-criteria methodology to assess the lighting performance and visual comfort as well as improving measures are proposed, including qualitative survey through questionnaires, quantitative study through field measures and lighting simulation (Chapter 13).

The **third section** deals with the results and discussion regarding the thermal performance of educational buildings under current and future climatic conditions (Chapter 14), the thermal performance of educational buildings under current and future climatic conditions using retrofit approaches (Chapter 15), the cost-effectiveness of adaptation measures (Chapter 15), the indoor air quality and the impact of natural ventilation under current climatic conditions (Chapter 16) and the natural lighting performance and visual comfort, and lastly, the proposed improvements based on current climatic conditions (Chapter 17).

In the **conclusion** (Chapter 18), regulatory level guidelines of retrofit approaches for the improvement of comfort and energy behaviour of educational buildings are provided for exploitation from the appropriate stakeholders.

## 1.7. Chapter Summary

This chapter provides an introduction to the thesis and the significance of this research. This introductory chapter identifies a gap on indoor environmental quality in educational buildings, both in the current and future climatic conditions and suggests the research to fill this gap. The chapter sets out the research aims, and concludes with an outline of what has been done in this thesis to contribute to the existing knowledge of the evaluation of comfort in school settings and on the holistic approach interventions. The next chapter presents a review of the current literature related to this thesis.

# PART A. RESEARCH BACKGROUND AND LITERATURE REVIEW

The Part A examines the research background of the legal energy context and reviews the existing literature about thermal comfort, air quality, natural lighting, climate change observation and projection, as well as possible technical solutions and cost effectiveness for the achievement of required overall comfort conditions.

# Chapter 2. General historic and legal energy context

## 2.1. Introduction

Buildings are responsible for approximately 40% of the EU energy consumption and 36% of the $CO_2$ emissions. Buildings are therefore the single largest consumer in Europe. At present, about 35% of buildings in the EU are over 50 years old, and almost 75% of the building stock is energy inefficient [41]. The purpose of this chapter is to review the energy performance of buildings in Europe in order to understand the necessity of energy retrofitting of existing building stock, describe the legislative framework and directives for climate strategies and targets set from the EU, and review the Cyprus energy policy for achieving energy and environmental goals. Finally, a chapter summary is provided.

## 2.2. Energy performance of buildings in Europe

The existing building stock generally has poor energy performance and is responsible for a significant amount of $CO_2$ emission sources in Europe. While new buildings can be constructed with high performance levels, it is the older buildings, representing the vast majority of the building stock which are predominantly of low energy performance and subsequently in need of renovation work. With their potential to deliver high energy and $CO_2$ saving as well as many societal benefits, energy-efficient buildings can have a pivotal role in a sustainable future [13].

### *2.2.1. European building stock*

Europe has the highest building density (building floor space over land area) compared to China and the US. Several factors are linked with the floor space trends such as wealth conditions, culture and land availability. The increasing trend in floor space over the years is associated with increased energy demand which in turn underlines the necessity for improving the energy efficiency of the existing building stock. In Europe the floor space per capita varies from country to country. According to the study undertaken by the BPIE in 2011 [13] which divided European countries based upon climatic, building typology and market similarities into three regions i.e. North & West, South and Central & East, half of the total estimated floor space is located in the North & West region of Europe while the remaining 36% and 14% are contained in the South and Central & East regions, respectively.

Source: BPIE survey

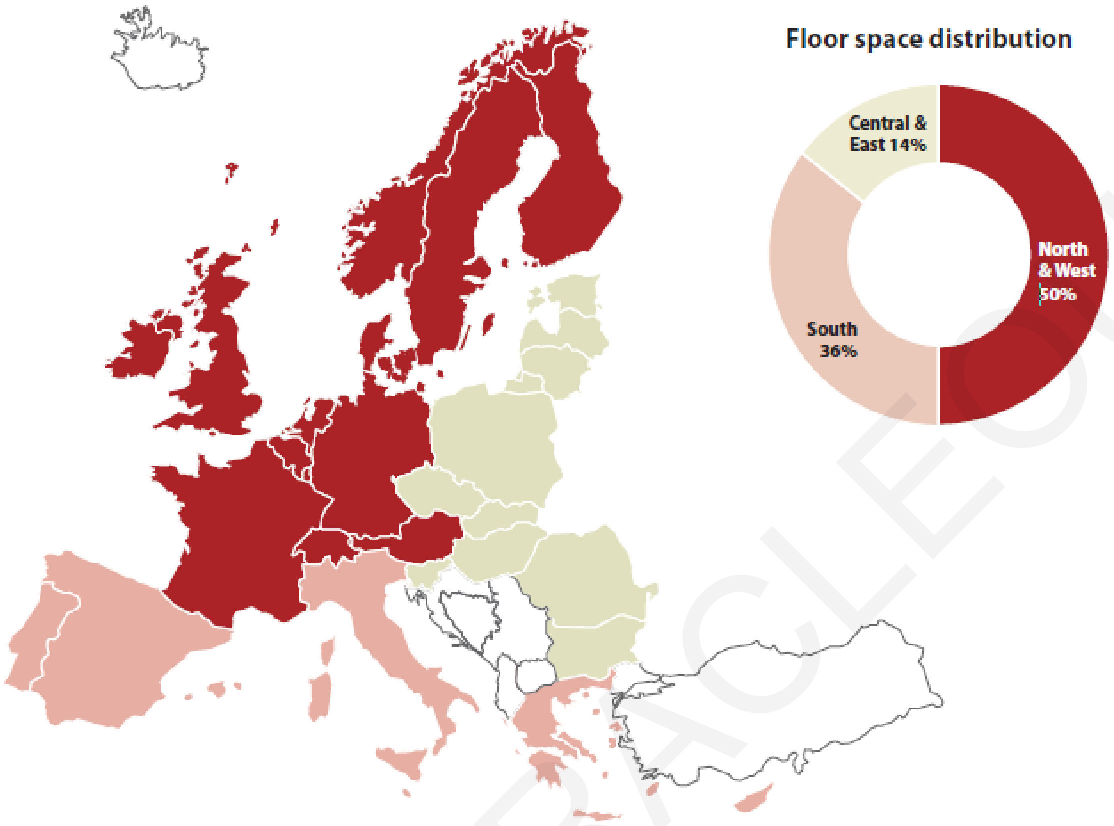



Figure 2.1. A representation of the European building stock [13].

### *2.2.2. Typology of buildings in Europe*

The building sector is usually divided into residential and non-residential which covers offices, educational buildings, hospitals, hotel and restaurants, sport facilities, wholesale and retail trade services buildings, and other type of energy-consuming buildings.

Non-residential buildings account for 25% of the total stock in Europe and comprise a more complex and heterogeneous sector compared to the residential sector. The retail and wholesale buildings comprise the largest portion of the non-residential stock while office buildings are the second biggest category with a floor space corresponding to one quarter of the total non-residential floor space. Similar usage pattern as offices are found in educational buildings which count for less than 20% of the entire non-residential floor space. State-owned buildings represent about 10-12% of the area of the EU building stock.

In general, the BPIE survey shows that currently there is limited knowledge on the European public building stock (and non-residential building stock in general) as well as retrofitting processes. It is therefore important to gather more information about energy-related characteristics of buildings, their quantities, and the state of retrofitting through further studies and surveys.

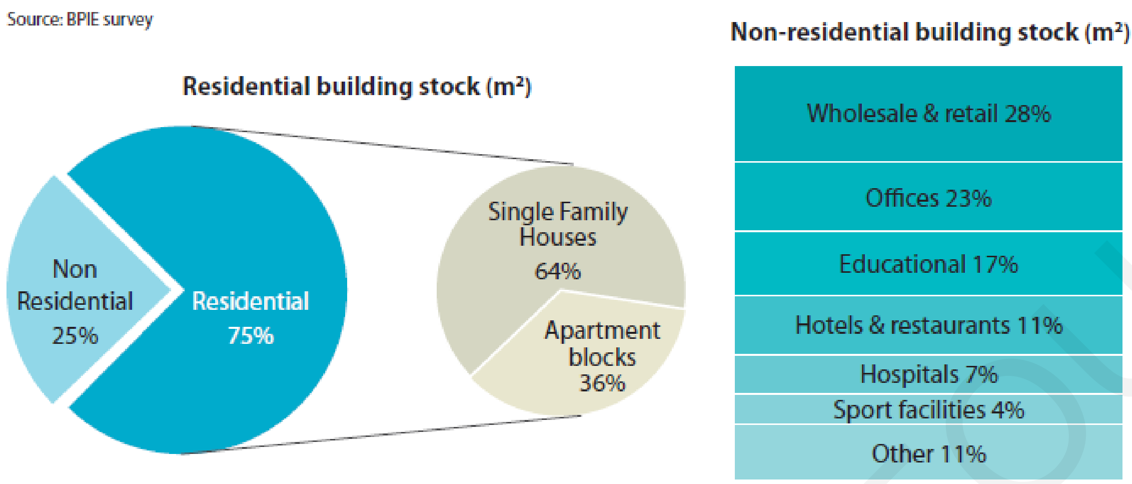



Figure 2.2. European buildings at a glance [13].

### *2.2.3. Age of building stock*

European buildings date from different time periods, even before the 1900s. The age of a building is likely to be associated to the level of energy use for the majority of buildings that have not undergone renovation for improving energy performance. The age of a building is also associated with the duration of the life cycle of the building. A substantial share of the stock in Europe is older than 50 years, with many buildings still in use today that are hundreds of years old. It is noteworthy that 38% of Europe's building stock was constructed before 1960 and 45% between 1961-1990 [13], where no energy performance standards were introduced and according to statistics, 70% of the current existing building stock is likely to be in use in 2050 [14]. Therefore, serious renovation action is needed in order to fulfil the essential requirements.

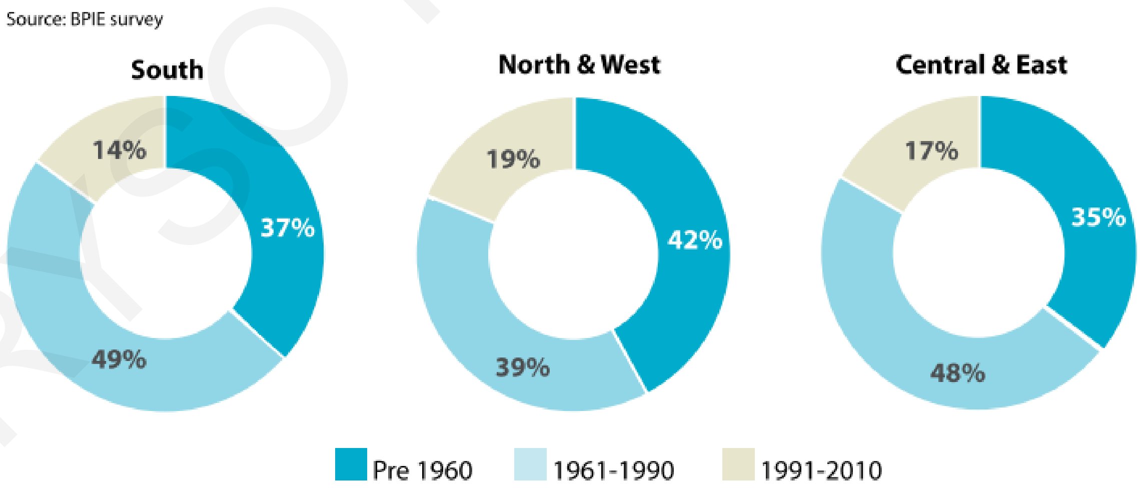



Figure 2.3. Age categorization of building stock in Europe [13].

### *2.2.4. Overall energy consumption in Europe*

Today, urban centres account for 80% of the population and consume 78% of the energy produced with the main sectors being buildings and transport. In the EU, the building sector is a fairly large end-user as it absorbs 40% of total energy consumption and is therefore suitable for implementing energy saving strategies.

Based on the database on energy efficiency indicators and energy consumption by end-use [42], there is an increasing share of the transport sector (from 30% in 2000 to 33% in 2015) and services (from 12 to 14%). The share of the industry sector has decreased by almost 6 percentage points, from 30% in 2000 to 24% in 2015, while for households the share is rather stable (27%) [42].

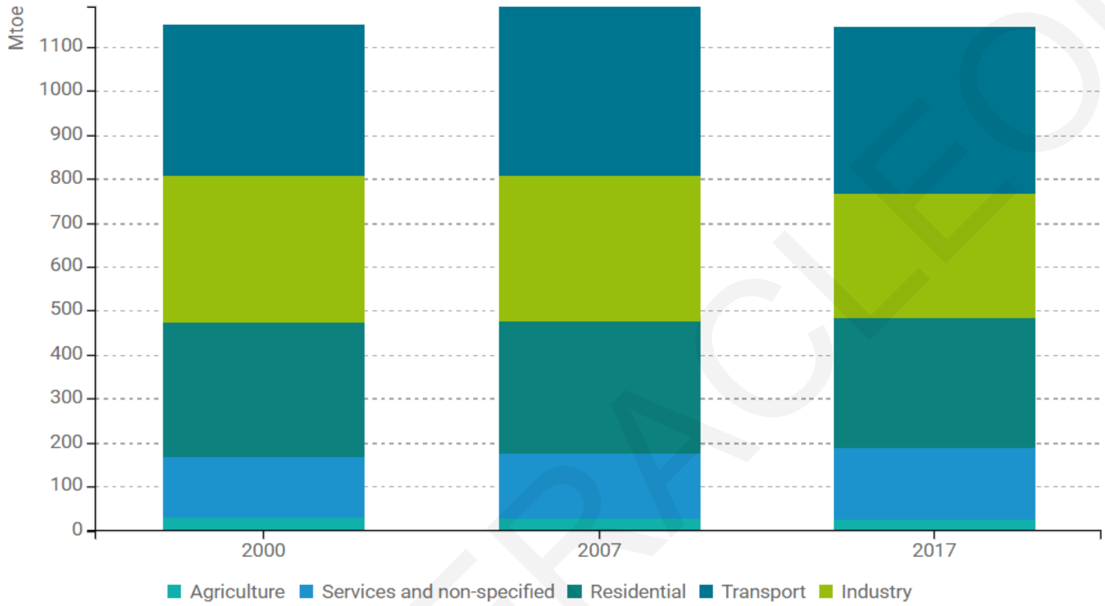



Figure 2.4. Final consumption by sector in Europe [42].

In EU countries, transport is generally the largest energy consumer sector, except in Germany, Sweden, Slovakia, Belgium, and Czech Republic where the industry sector has a greater role, and in Hungary, Latvia, Estonia where the residential sector is dominant. In Cyprus, transport is responsible for 55%, residential buildings for 19.1%, industry for 11.3%, services for 12.4% and agriculture for 2.2% of the final consumption in 2017 [42].

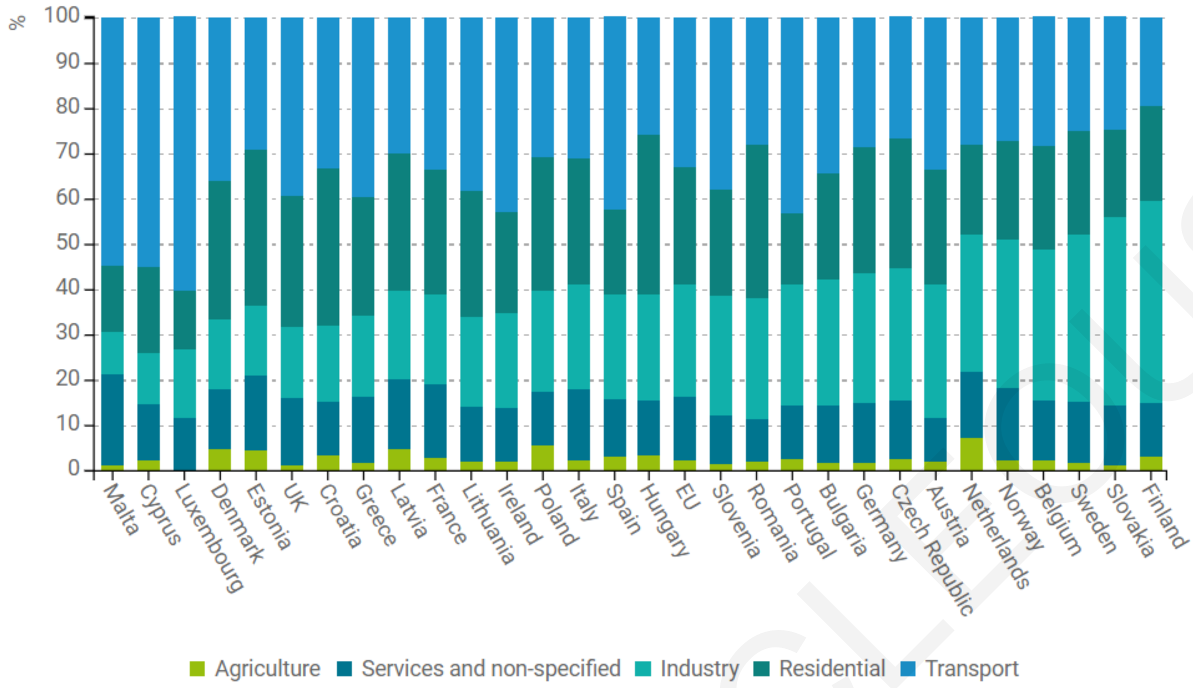



Figure 2.5. Distribution of final energy consumption by sector in each country [42].

### *2.2.5. Overview of Cyprus energy efficiency*

Cyprus has a small and isolated power system with no interconnections with other networks. It still has no domestic energy sources but only a minimal contribution from solar and is fully-dependent on energy imports. Prior to the EU accession in 2004, it did not implement an integrated energy policy for energy savings and had no building regulations with minimum energy efficiency requirements.

The fact that the thermal insulation of buildings was not institutionalized in Cyprus only until recently, make the potential savings resulting from the adoption of new thermal insulation measures particularly high. The long absence of mandatory thermal insulation regulations for new buildings in Cyprus has resulted in the construction of a large number of buildings with poor to moderate thermal behaviour and high energy needs to maintain comfort conditions, therefore resulting in high energy consumption. According to available statistics from 2011, 49% of the housing building stock has not taken any energy saving measures since 2011 and only 12% have some type of thermal insulation in the building envelope (Figure 2.6). The situation is somewhat better when it comes to windows, where more than 38% of houses have double glazing [43]. Generally, the same construction details are followed by all other building types in Cyprus.

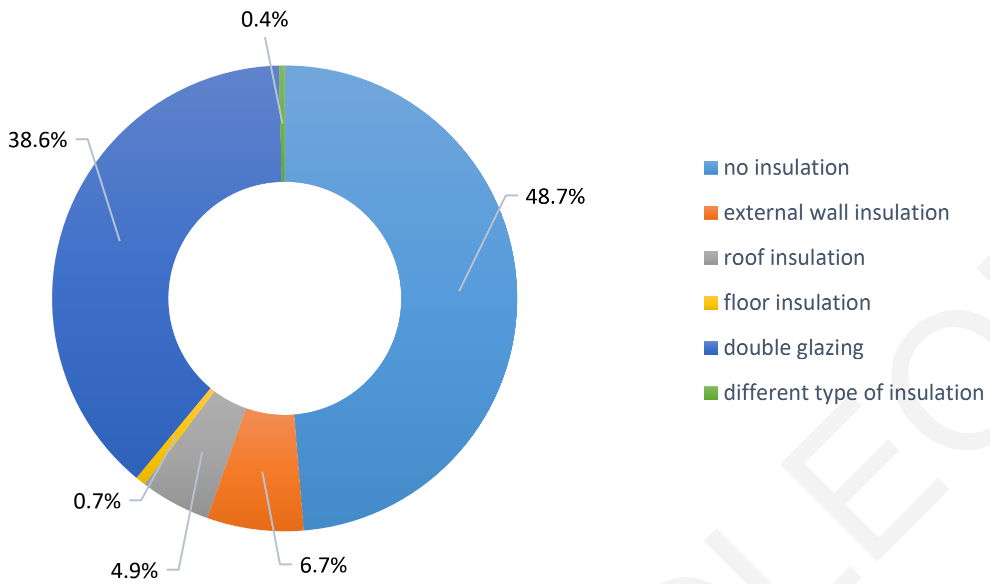



Figure 2.6. Percentage of residential buildings that have implemented thermal insulation measures [43].

Despite the temporary effects of the economic recession of years 2012-2015, energy consumption in Cyprus was higher in 2017 than in 2000. Increases in energy demand for both transport and buildings (residential and services) have been responsible for this development, while the share of the industry sector in energy consumption has dropped because of the its smaller share in the total economic activity of 2017, and thanks to energy efficiency improvements in major industrial plants [44].

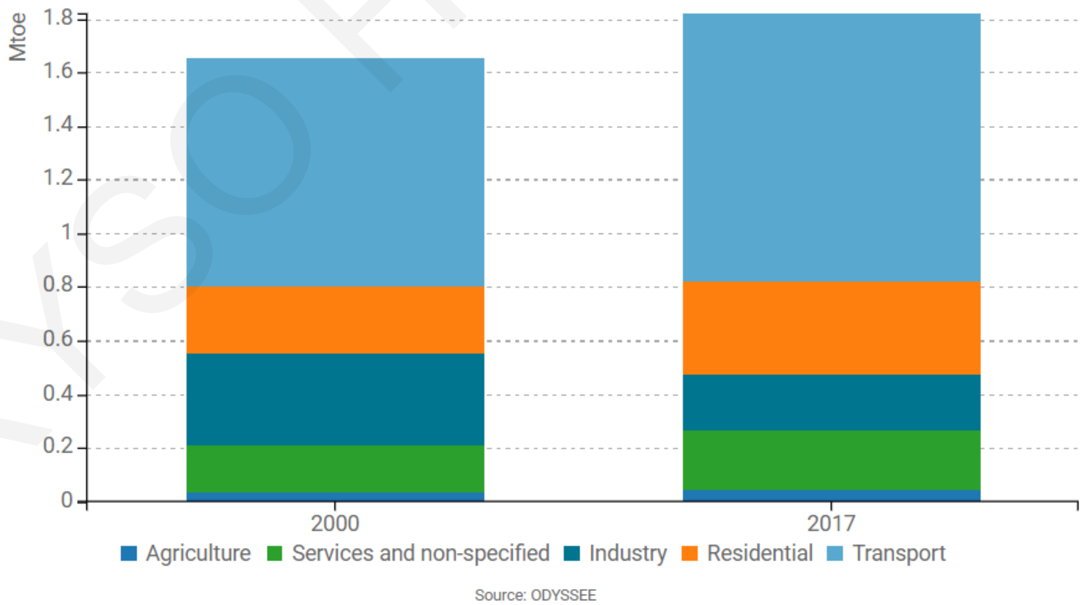



Figure 2.7. Final energy consumption by sector (normal climate) in Cyprus [44].

Overall, technical energy efficiency has improved by around 25% in Cyprus between 2000 and 2017. This has been driven by energy efficiency improvements in all sectors - buildings, industry and transport. Industry has shown the fastest increase in energy efficiency, mainly because the largest industrial energy consumer is by far the cement industry, which has undergone a major reconstruction and refurbishment of its plants. Transport has demonstrated the slowest energy efficiency improvement during 2000-2015; both road transport and air transport have been responsible for the lack of progress in energy efficiency. Over the recent years (2015-2017) progress in the service sector has remained stagnant too [44].

Energy efficiency in the building sector of Cyprus has improved steadily since the adoption of energy performance standards for new buildings in the mid-2000s, and as a result of the implementation of all relevant EU legislation. Still, energy consumption of buildings continues to grow as a result of the increasing number and size of buildings, which outweighs energy efficiency improvements [44].

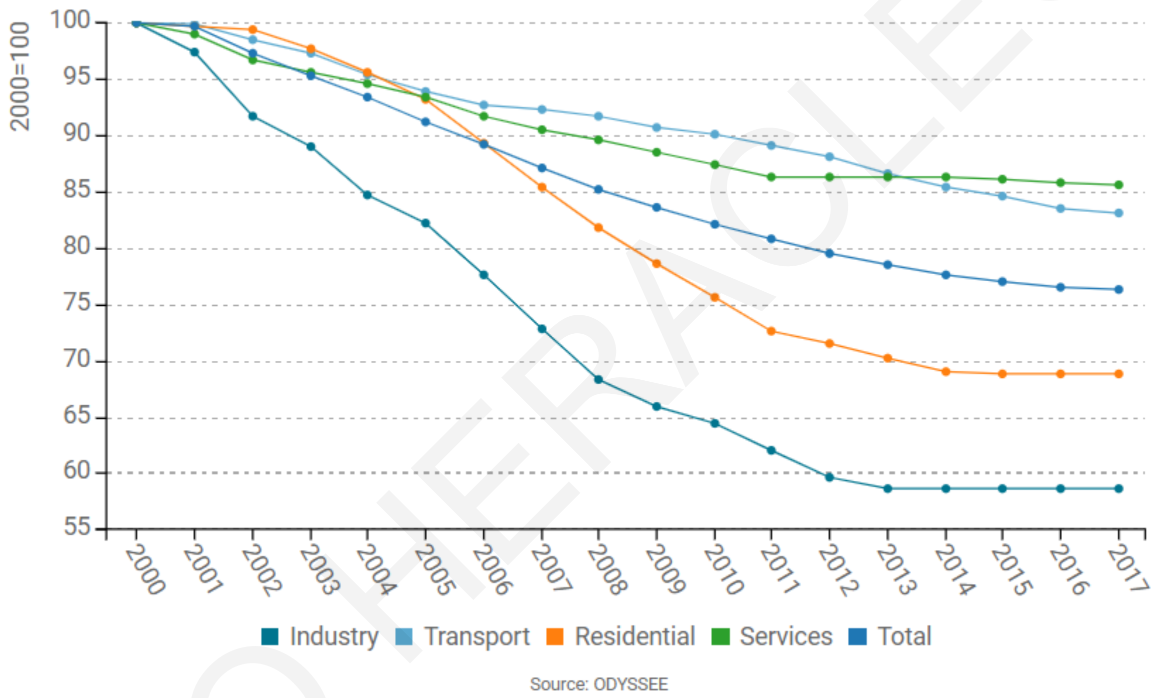



Figure 2.8. Technical energy efficiency index in Cyprus [44].

## *2.2.6. Energy performance of educational buildings*

Energy consumption of the public building stock represents an important cost in the energy balance of a state. Based on the literature, these buildings consume a large amount of energy because in the last 20 years, there was no energy saving measures for this type of buildings. Moreover, public buildings, particularly schools, should be buildings with elevated comfort levels because student and teachers spend much time in these rooms. The wellness and productive capacity of students and teachers are primarily affected by the comfort and air quality inside school classrooms.

Several studies investigated the typical yearly use of heating in schools [45], [46]. A study undertaken in educational buildings in Italy states that there is considerable amount of oil consumption that can be significantly reduced if appropriate energy measures and renewable energy sources are used [47]. The share of energy consumption for school buildings in the total energy consumption in the USA is 13%, for Spain 4% and for UK 10% [48]. A series of researches used energy auditing techniques to assess the energy performance of school buildings. Knowledge of the building energy consumption patterns is necessary to make comparative analyses and benchmarking of the actual consumption of individual buildings against others of the same typology using energy performance indicators [49], [50]. Moreover, this is helpful to identify whether the buildings are complying with the energy requirements [45].

Firstly, the overall energy performance of the building was influenced by the decisions made during the design and construction phase [49]. A study performed in Finnish educational building shows that in different educational building types, the newer buildings consume less heating. In the day care centres and school buildings studied, the primary heating consumption as a function of the age of the buildings has a decreasing trend. The energy performance of educational buildings in Europe is differentiated. Specifically, the typical annual heating consumption in European schools of Ireland, Slovenia and UK is 96 $kWh/m^2$, 192 $kWh/m^2$ and 157 $kWh/m^2$ respectively. Based on recent studies undertaken in Greek school buildings, the mean annual heating consumption varies from 31 $kWh/m^2$ to 67 $kWh/m^2$[51]–[53]. Another study states that the mean total energy consumption of 77 school buildings in northern Greece was 84 $kWh/m^2$ [54], while a study conducted in 159 schools in central Italy show an average annual consumption for space heating of 100 $kWh/m^2$ [45][47]. Another study in France indicated that 23.9 x $10^9$ kWh is consumed in educational buildings with the largest proportion of the total energy use of 87% occupied by heating and cooling, 6% by lighting, 3% by equipment and 4% all other uses. The major energy sources in educational buildings is oil with a share of 41% , then gas with 32%, followed by electricity with 14% and charcoal with 13% [55]. In Germany, Beusker, Stoy and Pollalis [56] examined the heating energy consumption of 105 schools in Stuttgart and found that the final energy range from 31 $kWh/m^2$/year to 205 $kWh/m^2$/year with average value of 93 $kWh/m^2$/year. In Torino in Italy, where the climate is continental with cool and dry winter and warm humid summer, a study was conducted in 120 schools and showed that the average energy consumption for heating is 100 $kWh/m^2$ [45].

Users play an important role in the overall performance of buildings, although it is an aspect which is least covered in the scientific literature. Understanding the interaction of users with buildings is significant to identify better design strategies to enhanced buildings' sustainability [57]. According to Christina et al. [45], organizational, social and behavioural issues are still among the areas that require further research. Additionally, Becker et al. [58] argue that further research is needed for the energy performance of school buildings, especially in the Mediterranean region.

To date, there has been almost no research related to energy performance of school buildings in Cyprus specifically. Exceptions are some researches presented in some conferences, and scientific journals [38], [59], [60]. Based on steady-state calculations, educational buildings built in 2009 where some energy requirements has been introduced, show final energy consumption between 40 $kWh/m^2$ and 150 $kWh/m^2$ with an average value of 70.24 $kWh/m^2$ [59]–[61]. However, these buildings do not represent the majority of the educational building stock and are therefore not representative cases. The majority of educational buildings were built before the energy performance requirements and therefore they have no insulation at all, causing poor indoor conditions.

The collection of data regarding the energy performance of educational buildings in Cyprus will create a database, which will be very useful to all interesting parties including academia, state technocrats and services and the construction industry. In addition, the correlation of energy consumption with indoor environmental quality affects the proper operation of buildings. In order to change the know-how, and to implement new methods that will save energy in the building sector, the necessary studies should be carried out so as to provide the basis for a decision-making methodology with the purpose upgrade the energy performance of educational buildings, the quality and comfort of the indoor environment.

## 2.3. Energy Policy in Europe

EU policymakers have long recognized the importance of energy-efficient buildings in mitigating climate change - starting with the Energy Performance of Buildings Directive (EPBD) and the Energy Efficiency Directive (EED) - but capturing that potential has posed a challenge. Specifically, the EPBD dominates the development in the field of energy policies in Europe since 2002 and it has been adopted and implemented by all 28 European Union Member States. Although several energy saving measures in the building sector have been adopted in central and northern European countries since the mid- 1970's, in the European south, actual measures where not adopted until the implementation of the EPBD. The reason for this time delay is due to the fact that in the European south, subtropical climatic conditions prevail, thus the energy consumption for heating is significantly reduced compared to the “cold northern region”.

The European Union has adopted policies in the field of energy saving in the building sector since the mid-1970s, following the October 1973 oil crisis, when the members of the Organization of Arab Petroleum Exporting Countries proclaimed an oil embargo. In September 1974 there was a resolution concerning a new energy policy strategy for the Community, when the Council accepted the objective of the “reduction of the rate of growth of internal consumption by measures for using energy rationally and economically without jeopardizing social and economic growth objectives” [62]. In May 1976 a Council recommendation on the rational use of energy in the heating systems of existing buildings was published [63]. In this recommendation, specific energy saving measures for existing buildings which are not occupied all the time and existing residential accommodation were introduced, including information such as recommended indoor temperatures of the considered spaces. Additionally, measures for the maintenance and inspection of heating systems as well as suggestions for improving the efficiency of hot-water systems in residential buildings, were proposed. This recommendation introduced for the first time the necessity for periodical inspection and service of heating systems with a capacity of 35 kW and above. In October 1977 a new recommendation on the regulation of space heating, the production of domestic hot water and the metering of heat in new buildings (77/712/EEC) was issued with further guidelines and suggestions in this field [64], including maximum temperatures for domestic hot water, and the use of building automation systems to regulate heating in buildings.

The first Directive of the European Union on the energy performance of buildings was published in 1993, entitled Council Directive to limit carbon dioxide emissions by improving energy efficiency (SAVE) [63]. The purpose of this Directive was the achievement by Member States of the objective of limiting carbon dioxide emissions by improving energy efficiency in the following fields:

- energy certification of buildings and the thermal insulation of new buildings,
- the billing of heating, air-conditioning and hot water costs on the basis of actual consumption
- third-party financing for energy efficiency investments in the public sector
- regular inspection of boilers,
- energy audits of undertakings with high energy consumption.

This Directive was followed by the 2002 Directive on the energy performance of buildings [65]. The 2002 Directive was much more detailed compared to the 1993 one, and introduced additional elements such as the necessity for adoption of a joint energy performance of buildings calculation methodology, the definition of energy performance of buildings minimum requirements, and specific energy performance measures for new and existing buildings. The 2002 Directive also adopted much more specific provisions for the energy performance certification of buildings. In this Directive revised conditions for the inspection of boilers were applied, and for the first time the requirement for the inspection of air conditioning systems was introduced. It is noteworthy to indicate that all policies until the beginning of the new millennium did not consider cooling as an important energy consumption sector, but the expansion of the EU to the south and the inclusion of countries such as Spain, Portugal, Greece, Cyprus and Malta eventually revised the approach of the Council. Member States brought into force the laws, regulations and administrative provisions necessary to comply with this Directive on January 2006 the latest.

The 2010 Energy Performance of Buildings Directive (EPBD) [66] and the 2012 Energy Efficiency Directive [67] constitute at present the main European legislations concerning the reduction of the energy consumption in the building sector.

Under the EPBD the following provisions are included:

- the energy class of the energy performance certificate of buildings must be announced in all advertisements for the sale or rental of new or existing buildings
- the EU member states should establish an inspection scheme for both heating and air conditioning systems
- all new buildings in the European Union must be nearly zero energy buildings by December 2020, and by December 2018 for public buildings

- the EU countries must set minimum energy performance requirements for new buildings and for buildings that will undergo major renovation and for the replacement or retrofit of building elements, including heating and cooling systems, roofs, walls, etc.
- the EU countries should draw up lists of national financial measures and tools to support the improvement of the energy efficiency of buildings
- The public sector in each Member State should lead the way in the field of energy performance of buildings, and therefore the national plans should set more ambitious targets for the buildings occupied by public authorities

The main novel element of the EPBD Directive and the major challenge of the European energy policy is the achievement of the nearly zero energy buildings targets. The nearly zero energy building is defined as the building which has a very high energy performance and uses energy from renewable sources in the same or similar rate it consumes energy on an annual basis. It is hence understood that the forthcoming policies should move into two directions: the reduction of the energy consumption of the buildings by means of more strict rules and legislations and the promotion of the green energy for the building sector, either produced onsite or off site [68].

Under the energy efficiency Directive (2012/27/EU), the following aspects are included which concern the energy performance of the building sector:

- EU should reach its 20% energy efficiency target by 2020. Under the directive, all EU countries are required to use energy more efficiently at all stages of the energy chain, including energy generation, transmission, distribution and end-use consumption.
- EU countries must make energy efficient renovations to at least 3% of buildings owned and occupied by central government on an annual basis
- EU governments should only purchase and rent buildings which are highly energy efficient
- EU countries must draw-up long-term national building renovation strategies which can be included in their National Energy Efficiency Action Plans.

In 2018, as part of the “Clean energy for all Europeans package”, the new amending Directive on Energy Efficiency (2018/2002) [69] and the Directive 2018/844 [70] was agreed to update the policy framework to 2030 and beyond.

The key element of the amended directive is a headline energy efficiency target for 2030 of at least 32.5%. The target, to be achieved collectively across the EU, is set relative to the 2007 modelling projections for 2030. Under the amending directive, EU countries will have to achieve new energy savings of 0.8% each year of final energy consumption for the 2021-2030 period.

The directive entered into force in December 2018 and needs to be transposed into national law by Member States by 25 June 2020. Under the Governance Regulation 2018/1999, Member States are required to draw up integrated 10-year national energy & climate plans (NECPs) outlining how they intend to meet the energy efficiency and other targets for 2030.

The framework for climate and energy for 2030 includes EU-wide targets and policy objectives for the period from 2021 to 2030. The targets were adopted by the European Council in 2018 and the key goals are:

- at least 40% cuts in greenhouse gas emissions (from 1990 levels)
- at least 32% share for renewable energy
- at least 32.5% improvement in energy efficiency

## 2.4. Energy Policy in Cyprus

Cyprus' energy policy is fully in line with that of the European Union, with the main focus on ensuring sound market competition, ensuring energy supply and meeting the country's energy needs with the least possible burden on the economy and the environment. The main chapters of the island's energy policy are:

- energy saving and efficient use of energy
- renewable energy sources
- industry and environment
- natural gas
- petroleum products and fuels
- electricity

The first **Minimum Energy Efficiency Requirements Ordinance**, issued on December 21, 2007, set for the first time maximum permitted thermal transmittance coefficients for new buildings and for buildings over 1000 $m^2$ undergoing large-scale renovation. Since 2010, all new buildings and buildings over 1000 $m^2$ undergoing large scale renovations are required to have at least Energy Class B in the Energy Performance Certificate as a minimum energy efficiency requirement. In 2013 maximum transmittance coefficients were reduced by 15%, and for the first time maximum thermal transmittance coefficients were set for building envelope elements that were replaced or retrofitted into existing buildings, regardless of whether large scale renovations were made or not. At the same time, a minimal percentage of the total energy consumption that must come from renewables for non-residential buildings has been set.

In 2016, the building thermal transmittance coefficients were further reduced in order to maximize the cost-benefit of the building life cycle, while minimum renewable energy rates in total energy consumption are mandatory for all types of buildings. According to the new Decree effective January 1, 2017, all buildings undergoing large-scale renovation must have an Energy Class Certificate of Energy equal to or better than B, to the extent technically and economically feasible. In July 1, 2020, the building thermal transmittance coefficients were further reduced in order to achieve nearly zero energy buildings.

According to section 15 of the Law, KDP 121/2020, the Minister of Energy, Commerce, Industry and Tourism by decree sets the minimum energy efficiency requirements for a building. The decree sets out the minimum energy efficiency requirements of a building for each new building and each new building unit as defined in Table 2.1.

Table 2.1. Minimum energy efficiency requirements of new buildings and new building units under the section 15 of the Law, KDP 121/2020.

| | **Description of the requirement** | **Requirement** |
|---|---|---|
| **1** | Energy efficiency class in the building energy performance certificate | A |
| **2** | Maximum primary energy consumption for residential buildings | 100 kWh/m$^2$/year |
| **3** | Maximum primary energy consumption for non-residential buildings except hotels | 125 kWh/m$^2$/year |
| **4** | Maximum primary energy consumption for hotels | 220 kWh/m$^2$/year |
| **5** | Maximum mean U-value of walls and load-bearing elements (beams, columns) | 0.4 W/m$^2$K |
| **6** | Maximum mean U-value of horizontal building elements (Folding floors, cantilever floors, roofs, roofs) and ceilings that are part of the building envelope | 0.4 W/m$^2$K |
| **7** | Maximum mean U-value of windows and doors | 2.25 W/m$^2$K |
| **8** | Maximum mean U-value of all building elements | 0.65 W/m$^2$K |
| **9** | Maximum mean shading factor of windows | 0.63 |
| **10** | Maximum heating demand for residential buildings | 15 kWh/m$^2$/year |
| **11** | Maximum average installed lighting power for buildings / units used as offices | 10 W/m$^2$ |
| **12** | It is allowed to exceed the maximum installed average of point (11) in the case that: | The building is equipped with an automation and control system which allows: (a) the continuous monitoring, recording, analysis and adjustment of the energy consumption for lighting (b) comparative evaluation of the energy efficiency of the building by identifying losses in the efficiency of the lighting systems of the building and informing the person in charge of the facilities or the technical management of the building regarding the possibilities of improving the energy efficiency |
| **13** | Minimum percentage of total primary energy consumption from renewable energy sources | 9% for hotels<br>25% for all other types of buildings |

The requirements for the minimum energy efficiency of a building for each building and each building unit that undergoes large-scale renovation are defined in Table 2.2.

Table 2.2. Minimum energy efficiency requirements for large-scale renovation under the section 15 of the Law, KDP 121/2020.

| | Description of the requirement | Requirement |
|---|---|---|
| **1** | Energy efficiency class in the building energy performance certificate for residential buildings | A |
| **2** | Energy efficiency class in the building energy performance certificate for non- residential buildings | Equal or better than B+ |

The minimum energy efficiency building requirements for a building element that is part of the building envelope or building unit, when installed or replaced or added to an existing building are specified in Table 2.3.

Table 2.3. Energy efficiency building requirements for a building element that is part of the building envelope or building unit, when installed or replaced or added to an existing building under the section 15 of the Law, KDP 121/2020.

| | Description of the requirement | Requirement |
|---|---|---|
| **1** | Maximum mean U-value of walls and load-bearing elements (beams, columns) | 0.4 $W/m^2K$ |
| **2** | Maximum mean U-value of horizontal building elements (Folding floors, cantilever floors, roofs, roofs) and ceilings that are part of the building envelope | 0.4 $W/m^2K$ |
| **3** | Maximum mean U-value of windows and doors | 2.25 $W/m^2K$ |

Pursuant to European Directive 2010/31 and the recently published Directive 2018/844 / EU amending key points of the former, Member States are required to adopt a methodology for calculating the energy efficiency of buildings. The main provision of the Directive is the proposed methodology to take into account the European standards issued on demand (Mandate) of the European Commission, based on the order M / 480, to support this project. The Republic of Cyprus with KDP 33/2015 published the methodology that is still in use. However, the publication by the European Committee for Standardization (CEN) of new and revised sets of standards creates the need to revise the existing methodology.

In order to comply with European obligations, the Energy Service of the Ministry of Energy, Trade, Industry and Tourism (contracting authority), as the competent authority of the Republic of Cyprus for the implementation of this Directive, is currently drafting a new Energy Efficiency Calculation Methodology for Buildings (MYEAK) which this thesis and its author are gladly contributing. It is noted that this new methodology will consider the provisions and guidelines resulting from the new and revised standards for the energy efficiency of buildings published by the European Committee for Standardization (CEN) under M / 480. In the absence of corresponding standards, the methodology will be supplemented by the use of scientifically substantiated calculation methodologies. In addition, data and provisions that are currently in force will be reviewed and supplemented in order to improve the quality of the existing framework.

### 2.5. Chapter summary

This chapter has presented a review of the energy performance of the buildings in Europe reviewing the European building stock, the typology, the age, the overall energy consumption and the energy performance of educational buildings. Additionally, a review of the energy policy both in Europe and in Cyprus has been performed.

Buildings account for approximately 40% of the energy consumption and 36% of carbon dioxide emissions in the EU. While approximately a third of the EU's building stock is over 50 years old, only just 0.4-1.2% is renovated each year. State-owned buildings represent about 10-12% of the EU building stock. Therefore, there is a significant potential for energy savings in this field that awaits to be tapped. The public sector can lead the way in efforts to increase the rate of renovations by prioritizing energy efficiency in its own buildings thus fostering the creation of necessary know-how in terms of new technologies and building methods.

That is the reason why in both the Energy Efficiency Directive (EED) and the Energy Performance of Buildings Directive (EPBD) the public sector's leading role and example-setting obligation is determined. In the EED this obligation focuses on an annual 3% renovation duty or, alternatively, an equivalent energy savings target for central government buildings. This allows for the development of national best practices and serves as a visible example for a wider public.

The energy performance of building stock in Cyprus, and especially educational buildings, is admittedly poor, since the energy efficient requirements was only introduced in 2007 in Cyprus. The large number of educational buildings as well as the large number of students concentrated in these spaces make schools important energy consumers. The improvement of the energy efficiency of this building type is necessary in the achievement of the EU-set framework for climate and energy for 2030.

# Chapter 3. A review of the literature about thermal comfort

## 3.1. Introduction

The purpose of this chapter is to develop a conceptual framework and build a theoretical basis for defining approaches to thermal comfort based on relevant literature. This chapter reviews the basic principles of thermal comfort and provides a context for the investigation of the relationship between the indoor environment and the thermal comfort of students in naturally ventilated buildings. To achieve the general purpose of the chapter, firstly the definition of the meaning of thermal comfort is provided associated with the parameters that affect the thermal comfort. Secondly, the study explores the existing approaches to thermal comfort widely used in academic research and describes the inclusion of these approaches in international and European standards. Moreover, a brief review of previous studies is provided related to the impact of thermal conditions on the performance of students, to students' thermal comfort in educational buildings in different climates, to the assessment of thermal comfort in educational buildings using different methodological approaches, and to the impact of natural ventilation on thermal comfort. Finally, the chapter is briefly summarised outlining its most important findings.

## 3.2. Defining the meaning of comfort

Various definitions of thermal comfort have been proposed in the literature. The term **comfort** is defined by European Council as the feeling of complete physical and mental well-being inside the building envelope [71]. **Thermal comfort** is described as a state in which there are no driving impulses to correct the environment by behaviour [72]. Givoni [73] defines it as the range of climatic conditions considered comfortable and acceptable inside buildings. This meaning implies an absence of any irritation or sensation of heat or cold discomfort. The most widely accepted definition of thermal comfort is suggested by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), which define it as 'that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation [74].

Thermal comfort is related to the need of the human body to maintain a stable core temperature of approximately 37°C, which is important for the overall health and the proper functioning of the body's organs, specifically the brain [71]. The interaction between the human body and the environment in maintaining this stability, a process called 'thermoregulation', is complex, and investigation requires the application of heat balance, physiological and psychological approaches [71]. As stated in the same study, physicists study how heat flows to and from the human body, thermal physiologists study body heat production and use, and thermal psychologists address conscious feelings about the environment. Building engineers and designers consider all of these influential factors in order to provide buildings that suit the thermal comfort requirements of people.

Olgyay [75] was the first to formalize the concept of thermal comfort for architectural purposes with his bioclimatic approach to architecture. Thermal comfort is a key objective in building design as part of providing an indoor thermal environment that is acceptable to occupants. Understanding thermal comfort is important to provide satisfactory conditions for people by providing a comfortable temperature, protecting people's heath and producing delight, to control energy consumption, and to suggest and set standards, guidelines and legislation for the indoor temperature [71].

The several of parameters that constitute the concept of comfort, make its clear qualitative and quantitative determination, complex. The term is directly related to environmental parameters, characteristics of structured space and data related to the psychosomatic characteristics of the user.

## 3.3. Thermal comfort influencing factors

Providing comfortable conditions depends on the factors that affect the occupant's thermal comfort. Indoor thermal comfort is highly influenced by six fundamental parameters: the four environmental variables of air temperature, mean radiant temperature, humidity, and air movements combined with two personal factors, the activity level and clothing of individuals [76]–[78].

### *3.3.1.Environmental parameters*

The **dry air temperature** of the air is the simplest indication of a cold or hot environment and is expressed in degrees Celsius (°C) or Fahrenheit (°F). The air temperature of the space is important sign much of the heat lost by the human body is excreted by air. It undergoes significant changes depending on the speed of the air and is affected by solar radiation, the surface temperature and the distance from them (Figure 3.1).

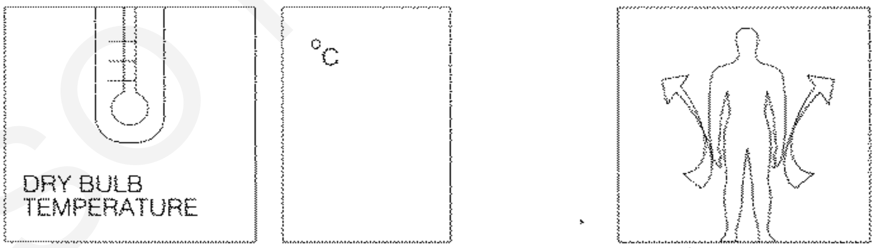



Figure 3.1. The dry bulb temperature as an environmental parameter that affects thermal comfort [38].

The **mean radiant temperature** has an important influence on the human body and corresponds to heat loss or gains from and to the environment by radiation [78]. The radiant temperature plays an important role in achieving thermal comfort (Figure 3.2). Direct exposure to radiation can cause the radiant temperature to be much higher than the air temperature.

The radiation of structural elements of school buildings can adversely affect thermal comfort. A masonry wall of school classrooms, without thermal insulation, exposed to sunlight during the cooling period, radiates a lot of heat resulting in a feeling of discomfort for the students near it. In addition, discomfort is created during the heating season due to low temperatures on the surfaces of the glazing and non-thermal insulated masonry.

The mean radiant temperature cannot be measured directly, but it can be approximated by globe temperature measurements. The globe thermometer is a matte black copper sphere, usually of a 150 mm diameter, with a thermometer located at its centre.

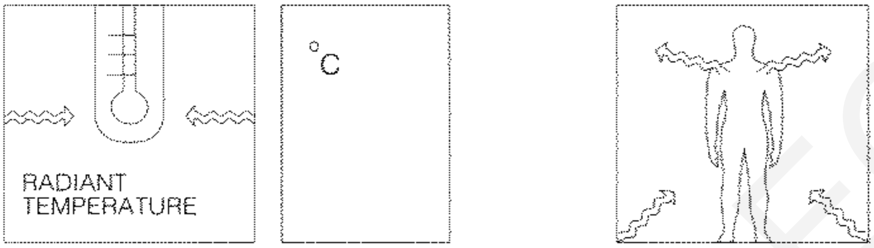



Figure 3.2. The mean radiant temperature as an environmental parameter that affects thermal comfort [38].

**Air movement** is measured by its velocity (v, in m/s) and it also affects the evaporation of moisture from the skin, thus the evaporative cooling effect [78]. If the air temperature is lower than the comfort temperature, increasing the air velocity increases the rate of heat loss to the environment and gives the feeling of cold air flow (Figure 3.3). Conversely, if the air temperature is higher than the comfort temperature, the increase in speed will increase the heat output from the convection coming from the environment.

It is common experience that air movement, be it a natural wind or generated by a fan, has a cooling effect. This largely depends on the velocity of that air movement. Under everyday conditions the average subjective reactions to various velocities are:

- $< 0.25$ m/s unnoticed
- 0.25-0.50 pleasant
- 0.50-1.00 awareness of air movement
- 1.00-1.50 draughty
- $> 1.50$ annoyingly draughty

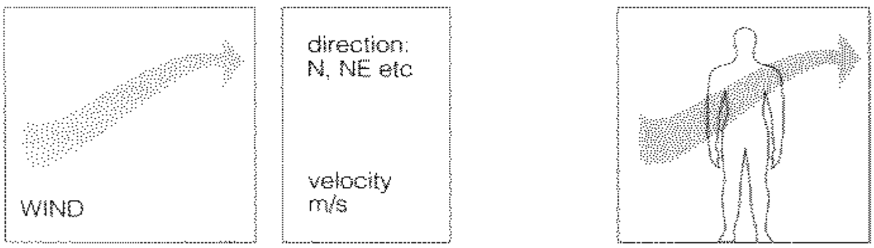



Figure 3.3. The air movement as an environmental parameter that affects thermal comfort [38].

Air Humidity also affects evaporation rate. This can be expressed by relative humidity (RH, %), absolute humidity or moisture content (AH, g/kg), or vapour pressure (p, in kPa) [78].

**Relative humidity** is the ratio of the percentage of moisture in the air to the humidity of saturated air at constant temperature and pressure (Figure 3.4). The desired relative humidity values of a space range between 40% - 50% and in extreme limits 30% - 70%. A percentage of less than 20% causes the mucous glands of the respiratory system to dry out, while mould formation is evident in humidity values of more than 80%. Humidity alone has a small effect on thermal sensation, but the combination of high humidity and high air temperature causes a feeling of discomfort. Additionally, high humidity reduces the heat loss of the body by evaporation and results in a reduction in the efficiency of sweating as a natural cooling strategy of the human body.

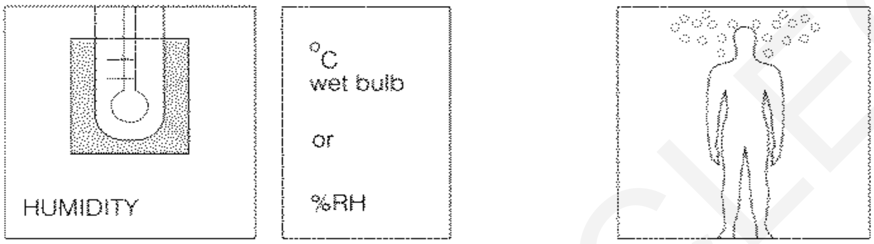



Figure 3.4. The relative humidity as an environmental parameter that affects thermal comfort [38].

### *3.3.2. Personal parameters*

**Metabolism** is the set of chemical reactions that take place in the body and are intended to maintain it at a constant temperature (36.7 °C). Energy production depends on the level of **activity** and ambient temperature. During the summer, there is a decrease in the amount of food (energy) and activities, so the chemical reactions of the metabolism are significantly reduced. Metabolic rate (met) is measured in watt per square metre of body surface area (W/ $m^2$). The metabolic energy is equal to 58 W/$m^2$ and expresses multiples of the average energy produced by a seated person at rest (Figure 3.5).

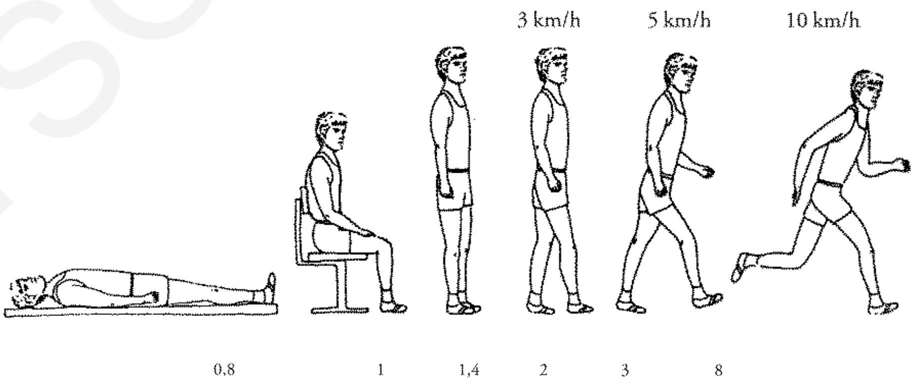



Figure 3.5. The metabolic rate for different activities [38].

**Clothing** is the insulating shell of the body, since during the exchange of heat between the surface of the skin and the atmosphere it functions as a thermal resistance (Figure 3.6). The thermal resistance of clothing is expressed in $m^2$k/w or in clo units, and varies from 0 clo for a nude body to approximately 4.5 clo for the heaviest arctic clothing [76]. It is noted that the degree of clothing depends on the seasonal temperature. Sudden changes in room temperature cannot be quickly compensated for by instantly changing students' clothing.

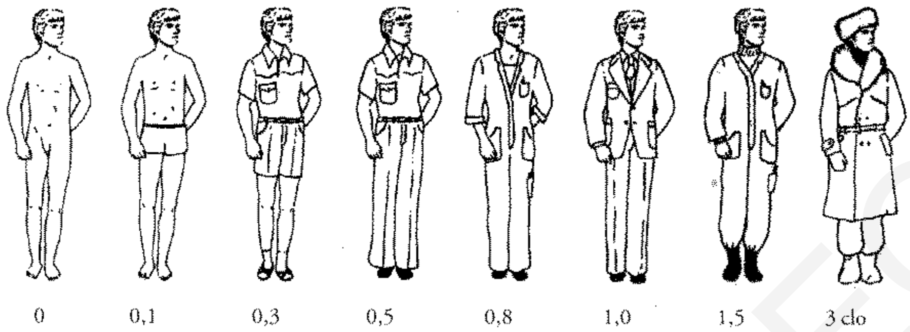



Figure 3.6. Clo value for different clothing [38].

**Human factors** that affect thermal comfort include gender, age, user habits, food and drink, body shape etc. It has been found that women set a higher comfort temperature than men, about 0.5 ° C, as there are differences in the metabolic rate between the sexes. Older people also want higher temperatures. This is due to the reduction of the metabolic rate, the reduction of activity, the change of eating habits and the physical condition of the individual. Similarly, the desired temperature for younger people, therefore at a higher metabolic rate, is reduced by about 0.5 °C. The outdoor temperature and psychological factors, such as occupants' perception of the thermal environment, expectations and past experiences, are significant in defining human thermal comfort [71], [79], [80].

## 3.4. Models of thermal comfort

There are several approaches describing thermal comfort; however, the most commonly utilized and underpinned in the existing literature are two: the rational or heat balance and the adaptive thermal comfort approach. These models have been developed over decades and have established thermal comfort standards and assessment methods [81], [82]. This section mainly reviews the literature on the heat exchange processes of the body, focusing on the classic thermal comfort approach, i.e., the steady-state PMV-PPD model [77] and the extension of this model [83], in addition to the adaptive comfort approach developed based on the theory of the human body's adaptation to indoor and outdoor climates [80], [84].

### *3.4.1. The heat balance approach*

The heat balance **approach** has been developed based on the physics and physiology of heat transfer to predict the thermal sensation and physiological response of the subject to the surrounding thermal environment [84]. Based on physiological thermal comfort models, the human body gains heat from metabolism and loses it due to respiration and evaporation. Additionally, depending on the physical environment, the body gains or loses heat by conduction, convection, and radiation [85]. The most widely used as a basis research in the field of thermal comfort is the work of Fanger in 1970 [77].

Fanger's PMV (Predicted Mean Vote) model is of particular significance as it provides the basis for many national and international comfort standards for evaluating thermal comfort, e.g. the ASHRAE Standard 55:2017 [86], the ISO Standard 7730:2005 [77], and the EN 15251:2007 (EN 16798-1:2019 is the update of the EN 15251:2007 standard) [87].

The PMV model was developed by Fanger during the second half of the 1960s from research and experimental work conducted in the laboratory and climate chamber with American and Danish college-age subjects [77], [88]. In these studies, the participants were exposed to various thermal conditions with standardized clothing while performing standardized activities that may have involved physical or mental work. In some experiments, the environmental conditions were chosen and measured by researchers while simultaneously the thermal responses of the subjects were recorded by asking their comfort votes on the commonly used seven-point psycho-physical ASHRAE thermal sensation scale ranging from cold (-3) to hot (+3), with neutral (0) in the middle. In other studies, subjects adjusted the thermal environmental condition to set the temperature until they felt thermally 'neutral'[89]. During the experiments, skin temperatures and the sweat rates of thermally comfortable participants were measured at various metabolic rates.

The PMV model combines four physical variables (air temperature, air velocity, mean radiant temperature, and relative humidity) and two personal variables (clothing insulation and activity level) into an index that can be used to predict thermal comfort. The index provides a score that corresponds to the ASHRAE thermal sensation scale, and represents the average thermal sensation felt by a large group of people in a space.

Table 3.1. The seven-point ASHRAE thermal sensation scale [74].

| **Corresponding term** | **Cold** | **Cool** | **Slightly cool** | **Neutral** | **Slightly warm** | **Warm** | **Hot** |
|---|---|---|---|---|---|---|---|
| **Thermal sensation** | -3 | -2 | -1 | 0 | 1 | 2 | 3 |

As stated by Fanger [77], [88], the human body perceives steady-state thermal comfort when the body is in heat balance, the mean skin temperature and sweat rate are within certain ranges, and no local discomfort exists in the environment. Local discomfort is caused by locally specific conditions, including local convective cooling (draughts), radiant temperature asymmetry, or the temperature gradients of the environment [90].

Fanger's model is built on the heat balance and thermoregulation theories, which assume that the body strives to keep thermal equilibrium during long exposures to a constant (moderate) thermal environmental condition with a constant metabolic rate [77]. It shows a balance between the rate of heat generation by the body and the heat dissipation from it with negligible heat storage within the body in this condition. According to these theories, the body maintains the balance between the heat generated by metabolism and the heat lost from it through physiological processes such as sweating, shivering, and regulating blood flow to the skin [90]. Fanger proposes the following formula:

$$H - E_d - E_{SW} - E_{re} - B = K = R + C \quad \text{(Eq. 3.1)}$$

where $H$ is the internal heat generation in the human body, $E_d$ is the heat loss by water vapour diffusion through the skin, $E_{sw}$ is the heat loss by evaporation of sweat from the surface of the skin, $E_{re}$ is the latent respiration heat loss, $B$ is the dry respiration heat loss, $K$ is the heat transfer from the skin to the outer surface of the clothed body (conduction through the clothing), $R$ is the heat loss by radiation from the outer surface of the clothed body, and $C$ is the heat loss by convection from the outer surface of the clothed body [77].

Fanger [77] expanded the comfort equation for the practical evaluation of a given thermal environment using experimental data covering 1396 subjects from Nevins et al. [91] and pooled with McNall et al. [92] and his extensive experiments. The expanded equation describes thermal comfort as the imbalance between the actual heat flow from the human body in a given thermal condition and the heat flow needed for optimal thermal comfort for a given activity level [89]. The relationship is given by Equation (3.2).

$$PMV = [0.303 \, \text{Exp}(-0.036 \times M) + 0.028] \times L \quad \text{(Eq. 3.2)}$$

where $M$ is metabolic rate, and $L$ is thermal load.

Furthermore, the PMV model provides a related index corresponding to the Predicted Percentage of Dissatisfied (PPD) with the indoor environment, which is simply an expression of the number of people who are dissatisfied and inclined to complain about the environment under which the measurements are taken. According to Fanger [77], the dissatisfied are defined as those who vote -2 (cool), -3 (cold), +2 (warm), or +3 (hot) on the seven-point ASHRAE sensation scale. Fanger shows a curve that illustrates the PPD in relation to the PMV; it is symmetrical and has a minimum of 5% dissatisfied for a mean vote of 0 (neutral). This point is considered the optimum condition for comfort. The relationship between the PMV and PPD indices is shown in Figure 3.7.

The PMV-PPD indices can be calculated using the following equations based on the ISO 7730 standard (ISO 7730, 2005) from the following mathematical function of eight quantities:

$$PMV = [0.303.Exp\,(-0.036.M) + 0.028 \begin{cases} (M-W) - 3.05x10^{-3}.[5733 - 6.99.(M-W) - p_a] \\ -0.42[(M-W) - 58.15] - 1.7x10^{-5}.M. \\ (5867 - p_a) - 0.0014.M.(34 - t_a) - 3.96x10^{-8}.f_{cl}. \\ [(t_{cl}+273)^4 - (t_r+273)^4] - f_{cl}.h_c.(t_{cl} - t_a) \end{cases} \quad \text{(Eq.3.3)}$$

where $M$ is the metabolic rate, in watts per square metre (W/m$^2$), $W$ is the mechanical work, in watts per square metre (W/m$^2$), $f_{cl}$ is the clothing surface area factor, $t_a$ is the air temperature, in degrees Celsius (°C), $t_r$ is the mean radiant temperature, in degrees Celsius (°C), $p_a$ is the water vapour partial pressure, in Pascal (Pa), $h_c$ is the convective heat transfer coefficient, in watts per square metre Kelvin [m²·K/W], $t_{cl}$ is the clothing surface temperature, in degrees Celsius (°C). The surface temperature of clothing, $t_{cl}$, is calculated as:

$$t_{cl} = 35.7 - 0.028.(M - W) - l_{cl}.\{3.96x10^{-8}.f_{cl}.[(t_{cl} + 273)^4 - (t_r + 273)^4] + f_{cl}.h_c.(t_{cl} - t_a)\} \quad \text{(Eq.3.4)}$$

where $I_{cl}$ is the clothing insulation, in square metres Kelvin per watt (m²·K/W). The convective heat transfer coefficient $h_c$ is:

$$hc = \begin{cases} 2.38.|t_{cl} - t_a|^{0.25} & for\ \ 2.38.|t_{cl} - t_a|^{0.25} > 12.1\sqrt{v_{ar}} \\ 12.1.\sqrt{v_{ar}} & for\ \ 2.38.|t_{cl} - t_a|^{0.25} < 12.1\sqrt{v_{ar}} \end{cases} \quad \text{(Eq.3.5)}$$

where $v_{ar}$ is the relative air velocity, in metres per second (m/s). The clothing surface area factor $f_{cl}$ can be calculated as:

$$f_{cl} = \begin{cases} 1.00 + 1.290.l_{cl} & for\ \ l_{cl} \le 0.078\, m^2.K/W \\ 1.0 + 0.645.l_{cl} & for\ \ l_{cl} > 0.078\, m^2.K/W \end{cases} \quad \text{(Eq.3.6)}$$

The PPD index can be calculated from the value of the PMV index using the following equation:

$$PPD = 100 - 95.Exp(-0.03353\ x\ PMV^4 - 0.2179\ x\ PMV^2) \quad \text{(Eq.3.7)}$$

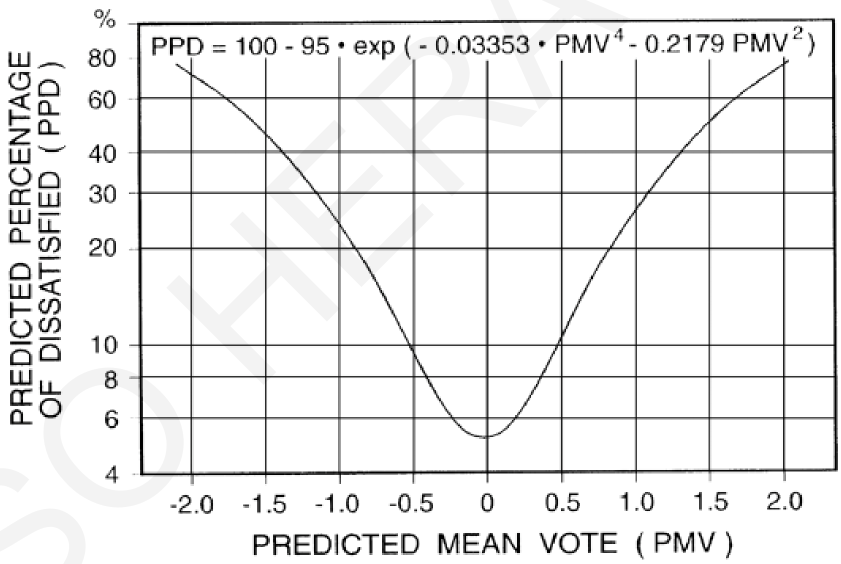



Figure 3.7. PPD index as function of PMV index [86].

### *3.4.1.1. Limitation and validity of the PMV model*

Due to the fact that the PMV model was introduced based on laboratory studies, several studies have been undertaken to examine the heat balance model in real climatic conditions. Numerous real-life field studies have brought the validity of the PMV model into question because the static thermal model essentially views the occupants as passive recipients of thermal stimuli [80]. Moreover, the model is unable to take into account the social and climatic factors that exist in real-world field survey [71]. In studies in warm, naturally ventilated buildings, it was found that the PMV model overestimates people's subjective sensation of warmth; however, in uniform and steady-state environmental conditions of air-conditioned buildings there is an agreement between the PMV predictions and the actual mean votes expressed on the thermal sensation [80], [93].

Humphreys and Nicol [94] examine the validity of the PMV model in predicting comfort votes in real-world circumstances because they believe that the exposure of a large group of people to a single thermal space with the same clothing insulation and the same level of activity rarely occurs. Their investigation has showed that predicted mean vote noticeably differs from the actual mean vote of occupants, in both naturally ventilated and air-conditioned spaces, and particularly in warm environments. They conclude that the PMV is valid for predicting the comfort response only under restricted conditions. According to Schellen et al. [95], the PMV model 'is applicable in situations where the indoor climate conditions are uniform, steady-state, close to neutral and where the individual occupants do not differ too much from each other.'

According to a study performed by Chamra, Steele, and Huynh [96], the activity level and clothing insulation are the two main input parameters that affect the uncertainty of the PMV model and that can contribute to discrepancies between the actual and predicted thermal sensations of occupants. This is also in line with the study of Humphreys and Nicol [94] who stated that metabolic rate and clothing is difficult to measure in real-world studies and depends on the climate and the cultures.

Furthermore, research has found discrepancies between the PMV model predictions and the occupants' actual thermal sensation responses due to the limitations of the model with regard to the differences in diverse subpopulations, such as the differences between the young and the elderly and between males and females [90], [97], [98]. The PMV model is primarily based on mathematical models developed for adult people and cannot be applied to children without corrections [90]. Parsons [98] notes that children are more sensitive to changes in the six primary parameters compared to adults. Moreover, gender may affect the perception of the indoor climate. Females are more sensitive to cold environments and less tolerant to deviations from the optimum conditions than males and generally prefer higher temperatures [97]–[100].

The other limitation of heat balance models is modelling the comfort response. The models make the assumption that 'there is some predictable comfort response for a given physiological state of the body' [101]. However, comfort perception is a psychological response, and other non-physical factors may affect it, e.g., expectations [101].

### *3.4.2. Adaptive comfort approach*

The **adaptive model** of thermal comfort is built on field-study research [102] conducted in real buildings, in situations of everyday life in which the subjects perform their normal activities [103]. The adaptive comfort approach investigates the dynamic relationship between occupants and their real-world environments [102], and it accounts for changes in the comfort temperature made by occupants' adaptation to their thermal environment. The designation 'adaptive' comes from a view of occupants as a primary factor of the comfort 'system' [104]. It is based on the adaptive principle that, 'if a change in the thermal environment occurs such as to produce discomfort, people react in ways that tend to restore their comfort'[105]. It is believed that people are not the passive receiver of thermal stimuli but rather are an active component of a dynamic system of people and their social and physical environments [105].

The adaptive comfort model was originated by Webb at the Building Research Establishment (BRE) in 1960s [106]–[108] along with his collaborators Humphreys and Nicol. In the 1970s, Humphreys found a relationship between indoor comfort temperatures and the mean temperatures inside buildings based on data from all of the available field studies on thermal comfort [109]. The indoor comfort temperature was shown to have an association with the mean monthly outdoor temperature at the time of the survey in free-running spaces [105], [110], [111]. Humphreys and Nicol [105] reveal that climate plays a significant role in the adaptive model. Moreover, it is suggested that cultural issues affect people's perception of thermal comfort; as Humphreys and Nicol [105] state, people from different parts of the world have different comfort temperature ranges. In that sense, past cultural and climatic experiences and expectations are influential factors in the actual thermal sensation and comfort of occupants [79].

Humphreys showed a difference between occupants in free-running buildings and those in heated or cooled buildings. Despite finding a linear relationship for free-running buildings, a more complex curvilinear relationship was shown for heated or cooled buildings [110]. The observed difference is mainly because of people's different expectations of those building types. Brager and de Dear [80] explain and discuss the role of expectations in the thermal adaptation of occupants in these two building types.

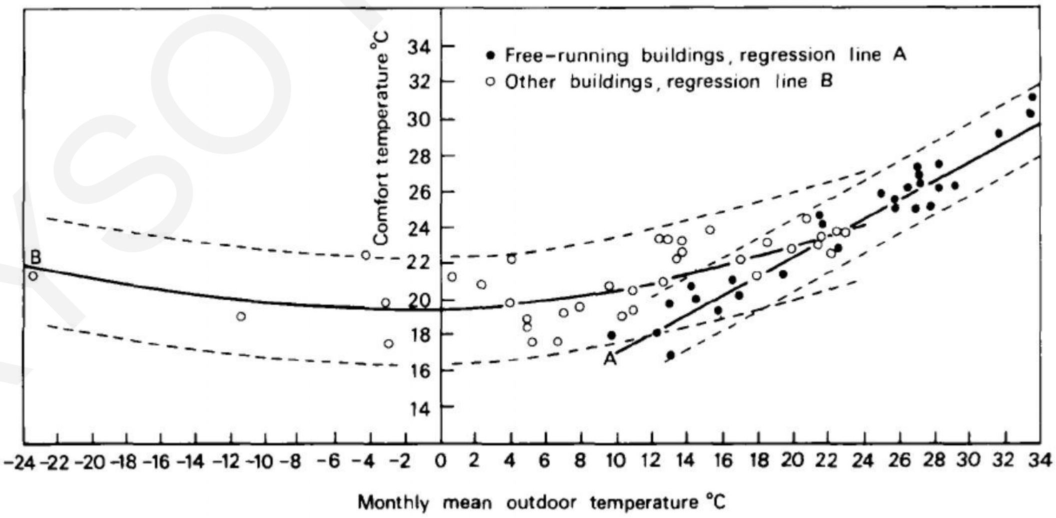



Figure 3.8 Humphreys' graph showing the indoor comfort temperature as a function of the monthly mean outdoor temperature (1978) [84].

The adaptive approach relates the indoor comfort temperature to the environment experienced by occupants [84], [112]. The strong relationship between the indoor comfort and the outdoor temperatures is the basis of the adaptive model [112]. The adaptive model predicts a comfort or neutral temperature ($T_c$), defined as 'the operative temperature[1] at which either the average person will be thermally neutral or at which the largest proportion of a group of people will be comfortable' [113]. Although the comfort temperature is calculated from the outdoor temperature, it is a function of further parameters. Additionally, there are limits to the range of indoor temperatures that people can adapt to over a certain period, which are related to people's thermal experience and physiology, which are affected by the climatic, the social, economic and cultural context [71]. Further, the clothing insulation [114] and the occupants' use of environmental controls [115] depend on the outdoor temperature.

The adaptive comfort model relates occupants' indoor comfort temperature to the prevailing outdoor temperature that they are experiencing, defined as the monthly mean outdoor temperature [116], the mean monthly effective temperature ET* [80], or the running mean outdoor temperature [117]. It should be noted that the methods for determining the indoor comfort temperature and the outdoor climate metrics are provided in detail in **Chapter 3.5.**

In the mid-1990s, de Dear and Brager developed an adaptive comfort model in an ASHRAE-sponsored project, based on good-quality data from thermal comfort field studies collected from various climate zones and seasons across the world [80]. The ASHRAE RP-884 project [80] underpinned the development of the adaptive thermal comfort international standards (see Chapter 3.5). The adaptive model was first adopted in the AHSRAE 55: 2004 comfort standard for naturally ventilated buildings [74], [81]. In 2007, the European adaptive standard, EN 15251:2007 [80], was published based on data from an exclusively European project named SCATS [117]; and in 2019 it was replaced by EN 16798-1:2019 [118] (see **Chapter 3.5**).

*3.4.2.1. Three categories of adaptation mechanisms*

De Dear and Brager [80] note that occupants' satisfaction occurs through appropriate adaptation to the indoor thermal environment. The term adaptation can be 'interpreted as the gradual diminution of the organism's response to repeated environmental stimulation' [102]. The conceptual basis of the adaptive model depends on several contextual and perceptual factors and psychological and behavioural processes. The adaptive mechanisms consist of three categories: physiological adaptation, psychological adaptation and behavioural adjustment [80], as described below:

***Physiological adaptation:*** Physiological adaptation includes changes in physiological responses that result from exposure to the thermal environment and that lead to a gradual decrease in the strain

[1] The operative temperature ($T_{op}$) is 'a uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment' [109]. It is a weighted average of the air temperature and the mean radiant temperature, where the weight is in proportion to the convective and the radiant heat transfer coefficients of the clothed human body [441].

made by such exposure [80]. It is mediated by the autonomic nervous system [119] and consists of the two subcategories of genetic adaptation and acclimatisation. Genetic adaptation is intergenerational, which means that it has evolved over a long time. Acclimatisation refers to the changes within the individual's lifetime in the settings of the body's physiological thermoregulation system, over several days or weeks, in response to the thermal environmental condition [119].

***Psychological adaptation:*** Psychological adaptation describes changed thermal perception in the form of thermal expectations based on past experiences [80], [81]. A lower thermal expectation of climatic conditions results in a reduction in the sensitivity of building occupants to temperature variations when they are exposed to a certain thermal condition over a given period. McIntyre [120] was one of the pioneers who acknowledged the role of experiences and expectations of indoor temperature. McIntyre [121] noted that 'a person's reaction to a temperature which is less than perfect will depend very much on his expectations, personality and what else he is doing at the time'. Although the psychological adaptation is the least investigated type of adaptive mechanism, it is considered the most obvious explanation for the discrepancies between predicted and observed thermal sensation [80].

***Behavioural adjustments:*** Behavioural adjustment refers to the actions that a person may take consciously or unconsciously to attain thermal comfort by changing his or her body's heat balance. Behavioural adjustment can be sub-classified into three categories: personal adjustment (e.g., modifying activity and posture, removing items of clothing, moving to different locations), technological adjustment (e.g., modifying the environment or surroundings by opening/closing windows or shades, controlling fans or turning on/off air conditioning systems), and cultural adjustment (e.g., taking a siesta in the heat of the day, schedule adjustments, adapting the dress code) [119]. Behavioural adaptation most likely offers the greatest opportunity for people to take corrective actions to maintain their thermal comfort when they feel uncomfortable.

According to a study undertaken by Humphreys [122], the most common personal adjustment by children in schools is the clothing adjustment, which is used to moderate changes in thermal sensation and to help themselves adapt to their classroom's thermal conditions as they are given no control over their physical environment.

*3.4.2.2. Occupant's control and satisfaction*

The ability of occupants to control their environment is important for their comfort and satisfaction level. Based on the literature, people who can control their environment are more tolerant of their environmental conditions. People are more forgiving of discomfort if they have some effective means of control over alleviating it. However, many contemporary buildings seem to move to the opposite direction. They take control away from the human occupants and try to place control in automatic systems, which then govern the overall indoor environment conditions, and deny occupants means of intervention [123], [124]. Paciuk [125] investigates how available control, perceived control, and exercised control influence the thermal sensation and comfort of occupants in office buildings in Israel during winter. According to Paciuk, perceived control has ‘a strong impact in shaping both thermal comfort and satisfaction outcomes’, whereas access to control opportunities substantially improves perceptions of control and indirectly affects satisfaction. The researches of Shahzad et al. [126], [127] conducted on Norwegian vs British open plan offices, reveal a 30% higher satisfaction and 18% higher comfort in buildings with higher percentage of thermal control (window, door, blinds, heating and cooling systems).

In a similar vein, Brager et al. [109] state that thermal sensation and preferences depend on the degree of control over their own environment. The study carried out by Brager, Paliaga, and de Dear [109] observed a 1.5°C difference in the comfort temperature between people who have high and low degrees of control over windows in their workplace. Based on another study by Kim and de Dear Dear [128], who examined the effect of personal control in the workspace, people with access to both operable windows and HVAC controls were the most satisfied with their environment, followed by occupants with access only to windows, then those with access to individual HVAC controls, and lastly those without access to either type of control. According to Nicol et al. [71], individual control seems to be more effective than group control.

*3.4.2.3. Difference between the results of the heat balance and adaptive approaches*

In naturally ventilated buildings, a discrepancy has been observed between the prediction of thermal comfort by the PMV model and the actual thermal perception of people [110], [119]. The adaptive approaches underscore the key role of occupants in making their thermal comfort state through physiological, behavioural and psychological processes (see **Chapter 3.4.2.1**), whereas the heat balance models view occupants in all building types and all climate zones as passive recipients of the thermal environment, as previously mentioned [119].

Although investigations of thermal comfort show a discrepancy between the findings of climate chamber studies and those of field research, Brager and de Dear [119] claim that ‘the adaptive and heat balance approaches to modelling thermal comfort are complementary rather than contradictory’. The heat balance model is regarded as partially adaptive because it accounts for some form of behavioural adaptation, e.g., changing clothing and the metabolic rate. Brager and de Dear [119] note that thermal sensation responses in naturally ventilated buildings differ from those in air-conditioned buildings. They suggest that occupants of naturally ventilated buildings have expectations of a wider range of comfortable temperature compared to occupants of air-conditioned buildings.

Based on a study performed by de Dear and Brager [81], a steeper regression slope of the observed responses is observed in naturally ventilated buildings than in HVAC buildings. In addition, the responses from users in HVAC buildings closely followed the PMV prediction, whereas the responses of occupants in naturally ventilated buildings were differentiated. According to the same study, occupants of HVAC buildings are more adapted to the narrow, constant conditions typically found in air-conditioned buildings, whereas occupants of naturally ventilated buildings prefer a broader range of temperatures that most likely reflect outdoor climate patterns (Figure 3.9). This comparison showed the impact of thermal adaptation on thermal perception in the two building types.

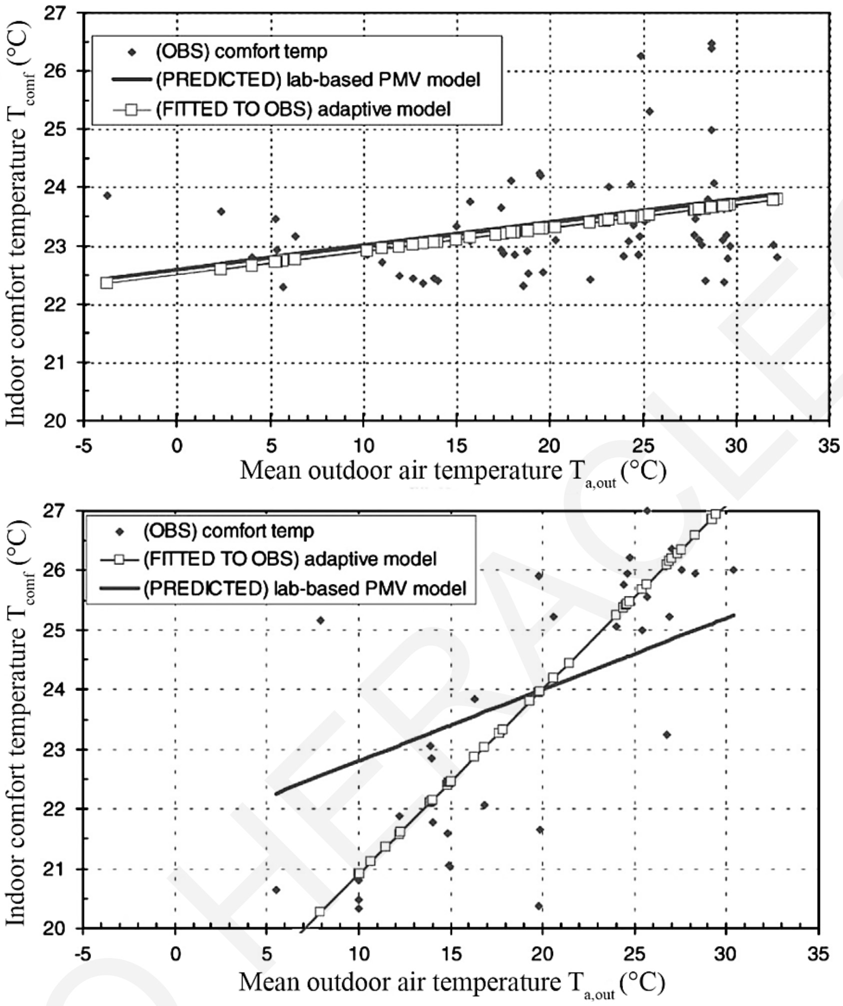



Figure 3.9. Comparison between observed and predicted comfort temperatures, for (a) HVAC buildings and (b) NV buildings [81].

*3.4.2.4. Strengths and weaknesses of the adaptive model*

The adaptive model provides a broader range of acceptable conditions for naturally ventilated buildings compared to the PMV model as the outdoor temperature increases. This is attributed to the fact that occupants can control their environment using the operable windows than in the centrally controlled HVAC buildings [104]. The adaptive model is important for both thermal comfort and energy saving. Humphreys et al. [102] and Nicol and Humphreys [129] state that when the adaptive comfort approach is used to guide the formulation of thermal comfort standards in buildings, the energy use for heating and cooling is reduced without compromising the occupants' thermal comfort or wellbeing.

Despite the strengths of the model, there is a criticism that the adaptive model focuses on the operative temperature to calculate the comfort temperature from the outdoor temperature while overlooking the effect of the four conventional indoor thermal factors, clothing, and activity level, which have a well-known influence on the human heat balance and thermal sensation [83]. However, Humphreys and Nicol [94] argue that the inclusion of these variables can result in systematic biases in the assessment of the thermal environment. Consequently, Humphreys et al. [102] consider the air temperature or the operative temperature to be a sufficient index for the assessment of the sensation of warmth.

As acknowledged by the ASHRAE 55:2017 and the EN 15251:2007 (revised in 2019 with EN 16987-1:2019) standards, air movement affects the comfort temperature, as elevated air movement extends the upper limit of the acceptable operative temperature for comfort in naturally conditioned spaces. Nicol [130] describes how air movement and the humidity of air affect the comfort temperature; these are particularly significant in determining comfort in hot climates where evaporative heat loss predominates. Nicol [130] suggests that the comfort temperature level is increased where air movement is higher than 0.1 m/s and that air movement produced by a fan raises the comfort temperature by an average of 2 K in hot conditions. Nicol states that the increase in humidity mainly affects the width of the comfort zone. A newer study performed by Vellei et al. [131] which examined the influence of relative humidity on adaptive thermal comfort in 13 global locations found that the current model is shown to overestimate overheating by 30% and their model extends the range of acceptable indoor conditions. The study showed that the impact of relative humidity cannot be neglected and play an important role in mediating adaptive thermal comfort.

## 3.5. International standards for thermal comfort

There are three well-known standards that are widely used for the assessment of thermal comfort in the indoor environment:

- EN ISO Standard 7730:2005, Ergonomics of the thermal environment—Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria [86]
- ASHRAE Standard 55:2013, Thermal Environmental Conditions for Human Occupancy [132]
- EN Standard 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics [87] (replaced by EN Standard 16798-1:2019).

The review of international standards is of significance to understand the applicability of the adult-based comfort standards to students, and for defining acceptable indoor operative temperatures inside the school classroom.

### *3.5.1. ISO 7730*

The ISO 7730 international standard presents methods for the calculation and use of the PMV and PPD indices primarily based on the mathematical model of the heat balance developed by Fanger [77] on the basis of laboratory studies (see **Chapter 3.4.1**). ISO 7730 rests on the PMV-PPD equations to predict the thermal sensation and satisfaction of people in a moderate thermal environment. In addition to the thermal comfort condition for the whole body using the PMV-PPD index, ISO 7730 includes criteria for local thermal discomfort. The local discomfort is caused by (a) draught, which is calculated using the draught rate (DR), (b) the vertical air temperature difference between ankles and head, (c) warm or cool floors and (d) radiant temperature asymmetry, which is determined by the percentage of dissatisfied (PD) equations presented in ISO 7730 [86]. The standard tabulates the measured values of the thermal insulation for typical clothing garments and ensembles, and provides a table of the metabolic rates corresponding to different activities. It specifies three categories of buildings based on the PMV and PPD range, i.e., building categories of A, B and C when -0.2<PMV<+0.2 (PPD < 6%), -0.5<PMV<+0.5 (PPD < 10%), and -0.7<PMV<+0.7 (PPD < 15%), respectively (Table 3.2).

Table 3.2. Categories of thermal environment [86].

| **Category** | **Thermal state of the body as a whole** | | **Local discomfort** | | | |
|---|---|---|---|---|---|---|
| | **PPD (%)** | **PMV** | **DR (%)** | **PD (%)** | | |
| | | | | Vertical air temperature difference | Caused by warm or cool floor | Radiant asymmetry |
| **A** | <6 | -0.2 < PMV < +0.2 | < 10 | < 3 | < 10 | < 5 |
| **B** | <10 | -0.5 < PMV < +0.5 | < 20 | < 5 | < 10 | < 5 |
| **C** | <15 | -0.7 < PMV < +0.7 | < 30 | < 10 | < 15 | < 10 |

Note:
PPD is Predicted Percentage Dissatisfied
PMV is Predicted Mean Vote
DR is Draft rate
PD is Percentage of Dissatisfied due to local discomfort

The ISO 7730 standard provides the design criteria and acceptable operative temperatures for different types of buildings based on certain assumptions, using the typical activity level and clothing insulation values of 0.5 clo during summer and 1 clo during winter. For classrooms, with an activity level of 1.2 MET (ISO 7730, 2005), the standard suggests certain operative temperature ranges for the three categories of buildings (Table 3.3). Based on the standard, the operative temperature range of 23-26°C is the one recommended for classrooms with a normal level of expectations (category B) during the cooling season, while the range of 20-24°C is recommended during the heating season.

Table 3.3. Categories of thermal environment [86].

| **Standard** | **Clothing insulation** | | **Activity** | **Category** | **Operative temperature range for classrooms (°C)** | |
|---|---|---|---|---|---|---|
| **ISO 7730:2005** | **Summer** | **Winter** | | | **Summer** | **Winter** |
| | 0.5 clo | 1.0 clo | 1.2 MET 70 W/m | A, PPD<6 | 24.5 ± 1.0 | 22.0 ± 1.0 |
| | | | | B, PPD<10 | 24.5 ± 1.5 | 22.0 ± 2.0 |
| | | | | C, PPD<15 | 24.5 ± 2.5 | 22.0 ± 3.0 |

Although ISO 7730 has briefly acknowledged the issue of adaptation and extended acceptable environments in warm climates or during warm periods, it has not addressed the adaptive approach in free-running buildings, as included in the ASHRAE 55:2013 and EN 15251:2007 (or EN 16798-1:2019) adaptive comfort standards.

### *3.5.2. ASHRAE 55*

The American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) has sponsored and developed an international standard to determine the criteria required for thermal comfort [74]. The main purpose of ASHRAE Standard 55 is to specify the combinations of six primary factors: air temperature, radiant temperature, humidity, air speed, metabolic rate, and clothing insulation, that create acceptable indoor thermal conditions for a majority of occupants.

ASHRAE Standard 55 is mainly proposed for offices with sedentary or near sedentary physical activities, which are less than 1.3 MET, because it is based on the thermal comfort data derived from these environments. The application of the standard is permitted for other types of buildings and occupants ‘if it is applied judiciously to groups of occupants, such as those found in classroom situations.’ Nevertheless, no further explanation or significant information is provided regarding the thermal comfort requirements of children.

ASHRAE 55 reflects the interests of the HVAC industry regarding the evaluation of comfort and is similar to ISO 7730 on the basis of the PMV-PPD indices calculations for defining the acceptable operative temperatures for occupants in buildings that rely on HVAC systems [71]. In ASHRAE 55, occupants’ thermal comfort conditions are determined when -0.5<PMV<+0.5, which predicts PPD<10% (Table 3.4). The standard also contains information on local thermal discomfort that is in line with ISO 7730; however, it does not provide building categories for different levels of acceptability. Local discomfort adds 10% PPD to the discomfort predicted by PMV [74].

Table 3.4. Indoor thermal comfort requirements based on ASHRAE 55:2013.

| **Standard** | **Acceptable thermal environment for general comfort** | |
|---|---|---|
| ASHRAE 55:2013 | PMV range | PPD |
| | -0.5 < PMV < +0.5 | <10 |

Alongside the PMV-PPD approach for buildings with HVAC systems, the ASHRAE 55 of 2004 is the first international standard to adopt the 'adaptive approach' to define the acceptable thermal conditions in occupant-controlled naturally ventilated buildings in which the indoor temperature is principally regulated by means of the use of windows. Its adaptive method is based on the extensive work of de Dear and Brager [81] and the use of data from the ASHRAE RP-884 research project [80], [133]. An extensive analysis [80] shows that the thermal responses of occupants in free-running buildings largely depend on the outdoor temperature. Hence, the standard uses the relationship between the climate and comfort indoors to define acceptable indoor operative temperatures in naturally conditioned spaces (Equation (3.8)). These spaces must have no mechanical cooling system and no heating system in operation (ASHRAE 55, 2013). Further, occupants have activity levels that are less than 1.3 MET (near sedentary activities) and are free to adapt their clothing within a range of 0.5 to 1 clo.

The ASHRAE 55 acceptability limits are based on the comfort equation (Equation (3.8)) for naturally conditioned buildings derived from the worldwide ASHRAE database. The 80% acceptability limit ($T_c$ ±3.5°C) is implemented for typical applications for 80% of the occupants to be satisfied, and the 90% acceptability ($T_c$ ± 2.5°C) is used when a higher level of thermal comfort is required:

$$T_c = 0.31\ x\ T_{pma(out)} + 17.8 \quad \text{(Eq.3.8)}$$

$$T_{\text{lower 80\% acceptability limits}} = 0.31\ x\ T_{pma(out)} + 14.3 \quad \text{(Eq.3.9)}$$

$$T_{\text{upper 80\% acceptability limits}} = 0.31\ x\ T_{pma(out)} + 21.3 \quad \text{(Eq.3.10)}$$

where $T_c$ is the optimal operative temperature for comfort and $T_{pma(out)}$ is the prevailing mean outdoor temperature. The 90% limits can be determined by subtracting 1°C from each limit. The outdoor temperature index was initially defined as the mean monthly outdoor temperature in ASHRAE 55 in 2010 and has changed in 2013 to the prevailing mean outdoor temperature. It can be calculated by a simple arithmetic average of the mean daily outdoor temperatures for a time period between seven and 30 sequential days prior to the day in question. In the revision of the standard ASHRAE 55: 2013, weighting methods, which can include different forms of running mean temperature are permitted. The comfort equation is used when the prevailing mean outdoor temperatures range from 10°C to 33.5°C.

In the ASHRAE RP-884 database [134], climate data were mainly obtained from local measurements of meteorological data taken during the survey and long-term monthly averages from published sources. In the original analysis of the database, the outdoor temperature was expressed as the 'outdoor effective temperature' ($ET_*$) [81]. However, the adaptive comfort standard used the mean monthly outdoor air temperature as the index of the outdoor climate, defined as the arithmetic average of the mean daily minimum and mean daily maximum outdoor temperatures for the month in question [81]. The reason for this is because the monthly timescale has an advantage for practical reasons, given that it is widely available and familiar to practitioners. Furthermore, Humphreys et al. [135] state ‘it is more convenient to incorporate the humidity as a modifier of the comfort temperature rather than include it in the climate metric.’

Nonetheless, using the value of the monthly mean has been criticized [113]. The first reason is because it is open to misinterpretation of the month period, e.g., it could refer to the historical mean, the mean of 30 days before the day in question or the present calendar month. Moreover, it overlooks the variability of the weather within a month and between sequential years [71], which could affect the neutral temperature through adaptive actions such as clothing changes [113].

### *3.5.3. European Standard EN 15251:2007*

The European Standard EN 15251:2007 was developed by the Comité Européen de Normalisation (CEN) and was recently replaced by the EN 16798-1:2019. However, this thesis was proceeded with the EN 15251:2007, as the replacement was made after the analysis of the main results of the thesis study. The small differences are presented in this chapter.

“The European Standard is applicable where the criteria for indoor environment are set by human occupancy and where the production or process does not have a major impact on indoor environment.” The first edition of this standard was published in 2007 as EN 15251 and specifies the criteria for indoor environment, for design and energy calculations for buildings, and building service systems.

Similar to the ASHRAE Standard 55, the European Standard EN 15251 provides different criteria for assessing mechanically cooled buildings and buildings in the free-running mode. For the evaluation of the thermal environment in mechanically heated and/or cooled buildings, EN 15251 contains comfort criteria based on the PMV-PPD index, similar to ISO 7730, with assumed typical values of the metabolic rate and summer/winter clothing, as suggested by ISO 7730. Furthermore, it provides building categorisation and recommends indoor operative temperatures for the design of buildings, which is similar to the ISO 7730 building categories. A short description of the categories of EN 15251:2007 is shown in Table 3.5.

Table 3.5. Description of the applicability of the categories used for mechanically conditioned (PMV-PPD) and free-running (K) buildings (EN 15251:2007) [87].

| **Category** | **Explanation** | **Limitation PMV** | **Limitation PPD (%)** | **Limitation K** |
|---|---|---|---|---|
| **I** | High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons | -0.2< PMV <+0.2 | <6 | ±2 |

| | | | | |
|---|---|---|---|---|
| **II** | Normal level of expectation and should be used for new buildings and renovations | -0.5 < PMV <+0.5 | <10 | ±3 |
| **III** | An acceptable, moderate level of expectation and may be used for existing buildings | -0.7< PMV <+0.7 | <15 | ±4 |
| **IV** | Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year | PMV<-0.7; or +0.7<PMV | >15 | - |

For free-running buildings, an adaptive standard similar to that in ASHRAE 55 is used for assessing the thermal environment. However, the thermal comfort criteria in this standard are based on the European project named Smart Controls and Thermal Comfort (SCATs) [117]. The main purpose of the SCATs project was to provide a method to decrease energy use in air-conditioned buildings based on the principles of adaptive comfort theory [117]. This project was a study of the indoor environment with approximately 5000 thermal comfort responses accompanied by indoor environmental measurements collected in 26 office buildings located in five European countries, i.e., the UK, France, Portugal, Sweden, and Greece, at monthly intervals over approximately one year [117]. In this project, a different adaptive algorithm was derived for each participating country.

The analysis of the data followed a number of lines of enquiry. First, it was used to provide a potential algorithm for the adaptive control of heated and cooled buildings. To extract the relation between the climate and comfort indoors, comfort temperatures were estimated from the data, using the Griffiths method. In essence the Griffith constant can be thought of as an educated guess of the rate-of-change in a sample of Actual Mean Vote (AMV) of building occupants with respect to operative temperature inside the room, with no thermal adaptation by the occupants [136]. The values of the running mean of the outdoor temperature ($T_{rm}$) were calculated using the exponentially weighted running mean with a weighting-constant "a" of 0.8. It was found that, below an outdoor temperature of 10°C, the comfort temperature ($T_c$) was approximately constant, while above 10°C the comfort temperature increased with outdoor temperature. The comfort temperature that is also proposed in EN 15251 for naturally ventilated buildings, is calculated using the following equation:

$$T_c = 0.33T_{rm} + 18.8 \quad \text{(Eq.3.11)}$$

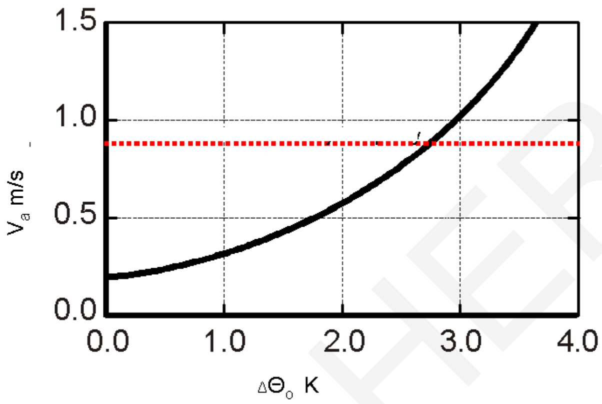
where, $T_c$ is the predicted comfort temperature when the running mean of the outdoor temperature is $T_{rm}$. The prevailing mean outdoor air temperature ($T_{rm}$) is the arithmetic average of the mean daily outdoor temperatures over a period of seven consecutive days prior to the day in question. The accepted indoor operative temperature range is provided for buildings without cooling systems. The acceptability bandwidths for the three building categories used in EN 15251: 2007 are Tc ±2°C, Tc

±3°C and Tc ±4°C for categories I, II and III, respectively. The comfort equation is used when the prevailing mean outdoor temperatures range from 10°C to 30°C (Table 3.5).

$$T_{lower\ acceptability\ limit\ of\ category\ II} = 0.33T_{rm} + 15.8 \quad \text{(Eq.3.12)}$$

$$T_{upper\ acceptability\ limit\ of\ category\ II} = 0.33T_{rm} + 21.8 \quad \text{(Eq.3.13)}$$

Under ‘summer comfort conditions’ (indoor operative temperatures > 25 ºC) increased air velocity may be used to compensate for increased air temperatures. Where there are fans (that can be controlled directly by occupants) or other means for personal air speed adjustment (e.g. Personal Ventilation systems) the upper limits presented in Equation (3.13), can be increased by a few degrees. The exact temperature correction depends upon the air speed that is generated by the fan and can be derived from Figure 3.10. This method can also be used to overcome excessive temperatures in mechanically controlled buildings if the local method for controlling air movement (fan etc) is available.




$\Delta\Theta$o = Increase in operative temperature, K
*Va* = Air speed, m/s

Figure 3.10. Air speed required to offset increased temperature (EN ISO 7730). The air speed increases by the amount necessary to maintain the same total heat transfer from the skin. Acceptance of the increased air speed will require occupant control of device creating the local air speed.

The revised version of EN 15251:2007, i.e. EN 16798-1:2019, provides input values of different categories of indoor environmental quality and differentiate slightly the explanation for categorisation. The categories are related to the level of expectations the occupants may have. A normal level would be “Category II, Medium”. A higher level may be selected for occupants with special needs (children, elderly, persons with disabilities etc.). A lower level will not provide any health risk buy may decrease comfort according to the standard. Moreover, in the acceptable indoor temperatures for buildings without mechanical cooling systems, in all categories, the lower acceptability limit for buildings is extended by 1 °C, compared to the EN15251:2007, indicating that people tend to be more adaptive to lower temperatures (Table 3.6).

Table 3.6. Description of the applicability of the categories used for mechanically conditioned (PMV-PPD) and free-running (K) buildings (EN 16798-1:2019) [118].

| Category | Explanation | Limitation PMV | Limitation PPD (%) | Limitation K |
|---|---|---|---|---|
| **I** | High | -0.2 <PMV <+0.2 | <6 | +2, -3 |
| **II** | Medium | -0.5 <PMV <+0.5 | <10 | +3, -4 |
| **III** | Moderate | -0.7 <PMV <+0.7 | <15 | +4, -5 |
| **IV** | Low | -1.0 <PMV <+1.0 | <25 | - |

Moreover, the indoor operative temperature correction for increased air speed with fans or personal systems during the summer period has been slightly differentiated in the EN 16798-1:2019 and presented in Table 3.7.

Table 3.7. Indoor operative temperature correction (ΔΘo) applicable for buildings equipped with fans or personal systems providing building occupants with personal control over air speed at occupant level [118].

| Average Air Speed ($V_a$) 0.6 m/s | Average Air Speed ($V_a$) 0.9 m/s | Average Air Speed ($V_a$) 1.2 m/s |
|---|---|---|
| 1.2°C | 1.8°C | 2.2 °C |

### *3.5.4. Comparison between the adaptive comfort standards*

The RP-884 and SCATs databases are implemented in the global ASHRAE 55 and the European EN 15251 standards, respectively. The general approach used in the ASHRAE RP-884 and the SCATs project are broadly similar; both the ASHRAE Standard 55 and the EN 15251 provide linear regression equations that suggest the relationship between the prevailing outdoor climate and comfort indoors in naturally ventilated buildings. As noted in the review article by de Dear et al. [104], 'apart from a 1 K difference between the y-intercepts of the two standards' equations, they look remarkably similar'. In both cases, the comfort temperature is calculated from thermal sensation votes and the operative temperature, whereas the prevailing outdoor temperature is implemented in the final adaptive relationship between indoor comfort and outdoor temperatures. Nonetheless, there are some differences in their methods and the statistical details, some of which have been noted by Nicol and Humphreys [113], de Dear [136] and de Dear et al. [104]. These standards are compared in Table 3.8.

The geographical scope of the input data for the ASHRAE 55 was from the ASHRAE global database, whereas EN 15251 was built on data from the European field studies in the SCATs project. Hence, the exclusive focus on Europe reflects the intention of SCATS to be more directly applicable to a European standard [104], [113]. Furthermore, different methods have been used to determine the comfort temperature in each of the databases.

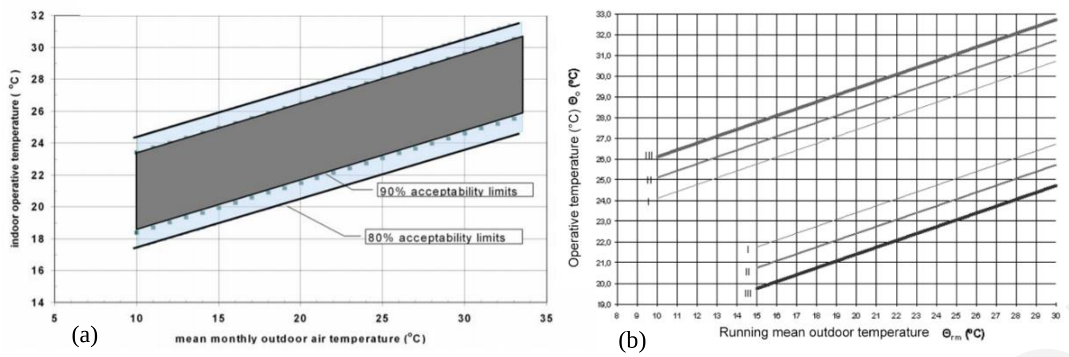
In the ASHRAE database, the individual building represents the unit of statistical analysis, whereas the comfort temperature is calculated from each individual interview in the SCATs database.

Thermal neutrality is derived for each building from statistically significant regression models in the ASHRAE database [80], [104], whereas in the analysis of the SCATs database, it is calculated for each comfort vote using the so-called ‘Griffiths method’ [113], [117], [135].

As Cyprus is part of Europe, the present study adopts the European Standard EN 15251:2007 for the analysis of the comfort conditions of educational buildings in Cyprus.

Table 3.8. Comparison of the adaptive comfort standards in free-running/ NV buildings [137].

| | **Standard** | |
|---|---|---|
| | **ASHRAE 55-2013** | **EN 15251:2007** |
| **Database** | ASHRAE RP-884: Data mainly from office buildings | SCATs project:<br>Data mainly from office buildings |
| **Unit of analysis** | Single building per season | Individual comfort votes |
| **Neutral temperatures** | Calculated per building per season using regression analysis | Assumed- Griffiths method |
| **Climate metric** | Mean effective temperature (ET*) | Exponentially weighted running mean temperature (Trm) |
| **Applicability** | Primarily for office buildings with sedentary activity level 1-1.3 MET | Offices and comparable building with sedentary activities 1-1.3 MET |
| **Building classification** | NV buildings<br>No mechanical cooling system in operation | Free running buildings<br>No mechanical cooling in operation |
| **Occupancy** | Occupants must be free to adapt their clothing | Occupants must be free to adapt their clothing |
| **Acceptable operative temperature range (°C)** | 90% accept: ±2.5<br>80% accept: ±3.5 | Category I:± 2<br>Category II:± 3<br>Category III:± 4 |
| **Outdoor climate index** | Prevailing mean outdoor air temperature | Exponentially weighted running mean temperature (α=0.8) |
| **Range of outdoor temperatures** | Prevailing mean outdoor temperatures of 10-33.5°C | Running mean outdoor temperatures of 10-30°C |
| **Equation** | $T_c = 0.31 \times T_{pma(out)} + 17.8$ | $T_c = 0.33 \times T_{rm} + 18.8$ |
| **Comfort band** | Defines limits for 80% and 90% satisfaction | Defines limits for class I, II, III comfort |
| **Access to window** | Operable windows are required | Easy access to operable windows |
| **Increase air speed** | The upper acceptable operative temperature limit can be increased by increasing air speed above 0.3 m $s^{-1}$, when operative temperature >25°C | The upper temperature limits can be increased by a few degrees due to air speed increments, when operative temperature > 25°C |
| **Adaptive comfort chart** | | |




Note: a: Acceptable operative temperature ranges for 90% and 80% acceptability in naturally ventilated spaces, after ASHRAE 55 (2013)
b: Acceptable operative temperature ranges for naturally conditioned spaces, after EN 15251 (2007)

## 3.6. Previous studies about thermal comfort

### *3.6.1. Previous studies about the impact of thermal conditions on the performance of students*

In recent years, the role of educational premises in creating a productive educational environment as well as to promote environmental awareness has been widely recognized. Hence, there have been several studies investigating educational buildings, highlighting that undesirable indoor environmental conditions negatively influence the learning abilities and performance of students [21], [31], [138]–[141]. Moreover, health and wellbeing issues are of high research interest, given that students spend one third of their time inside school buildings [142], [143]. Several studies have already been undertaken in different countries with different climates, stressing the importance of comfort in indoor spaces [144]–[147]. Although the human organism is very adaptive, students cannot perform well when their physical environment is uncomfortable [148], which implies that maintaining indoor temperatures within acceptable limits in classrooms is necessary to provide comfortable learning spaces for students. Cold or heat stress can cause thermal discomfort and reduce the motivation to apply effort to work [149]. The conclusions of some studies demonstrate that many classrooms do not perform as predicted during the design process in terms of their indoor environment conditions. Frontczak and Wargocki [150] studied the impact of different parameters on human comfort concluding that thermal comfort is the most significant factor in indoor environmental quality assessment and that occupants of naturally ventilated buildings engage in a more adaptive behaviour. According to a study undertaken by Mendell and Heath [21], there is good agreement between indoor conditions and the performance and attendance of occupants. They also derived to the conclusion that indoor conditions above 24°C tended to decrease the productivity of students. Another study of Pepler and Warner [151] conducted in school laboratories stated that learning efficiency rises when the temperature ranges from 17°C to 27 °C.

An experimental procedure, during which students were exposed to different conditions for two hours was conducted in Sweden by Wyon [152]. The performance of students was considerably reduced at higher indoor temperatures i.e. 27°C and 30°C, compared to 20°C. Authors highlighted that reading comprehension and reading speed decreased with increased temperatures. Similar results have been reported by Holmberg and Wyon [153], who recorded significantly improved performance of students when the classroom temperatures were dropped down to 20°C compared to higher temperatures. Park [154] studied a large amount of examination results from schools in New York demonstrating that the risk of failing the examination increased by 12.3% when the ambient temperature was 32°C, compared with the results obtained at 22°C. Furthermore, Lan et al. [155] state that increasing the temperature, in turn increases the blood gas concentration of $CO_2$, causing negative health effects, such as headaches together with low levels of concentration. On the other hand, Hancock and Vasmatzidis [156] state that there is a temperature range where people can tolerate thermal stress without compromising cognitive performance, due to psychological and physiological acceptability. Similarly, according to the Adaptive Thermal Comfort Model [157], thermal acceptability exists when there is no possibility of adjusting clothing insulation and air velocity; however, as shown above this can have a significant reduction in the performance of students. Finally, it should be noted that according to Wargocki and Wyon [149], it has not yet been defined whether the students' subjective acceptability of thermal discomfort is adequate to minimize the direct effects of physiological responses on performance, although this seems unlikely.

### *3.6.2. Previous studies in educational buildings using different methodological approaches*

There are several assessment approaches of thermal comfort both objective and subjective; with the most widely accepted being subjective evaluation. This approach covers individual feelings, sensations, preferences, and physical and personal comfort variables in a quantitative way. Subjective surveys with questionnaires use descriptive scales such as the seven-point ASHRAE for rating thermal sensation, the three-point McIntyre scale for thermal preference, and checklists for clothing and activity.

It is noted that the thermal comfort zone changes from one geographical space to the other according to the climate of the area under study, the geographical location, built environments and subjects. Thermal comfort is usually assessed using two main approaches (described in **Chapter 3.4**); the heat balance approach and the adaptive models. As abovementioned, several studies criticized the heat balance approach although the studies were conducted on college students within climate-controlled contexts [158]–[160]. Since the introduction of the adaptive comfort model, several researches have been developed in order to establish quantitative indexes which allow the user to enhance his/her comfort conditions [161]. The evaluation of thermal comfort using objective survey presupposes measurement of different physical parameters such as: air temperature, relative humidity, air velocity and radiant temperature as well as clothing and metabolic rate for the calculation of thermal comfort indices (i.e. Predicted Mean Vote (PMV), Effective Temperature (ET), and Operative Temperature (Top) in one point at sitting height (0.6–1.1 m) in the classroom [162]–[164].

Based on a review study of Zomorodian et al. [139], the majority of studies (50%) use the heat balance approach, but studies based on the adaptive comfort model have also increased in recent years (15%).

In addition, many studies (35%) used both methods to assess the thermal comfort condition and compared the results with each other. Several studies criticized the accuracy of the PMV as it shows discrepancies from the actual thermal sensation, in all climate zones and educational stages (Figure 3.11). Among the reviewed papers that used the rational comfort method, most (50.04%) reported that the model underestimates the students' thermal sensations, 35.71% reported overestimation, and only 14.25% reported that the thermal comfort predictions are compatible with the students' actual thermal sensations. Underestimation was mainly reported at primary levels while overestimation was observed at secondary and high school levels, while compatibility was only reported at university classrooms. In addition, results reveal that incompatibility is extreme in the temperate and tropical climates.

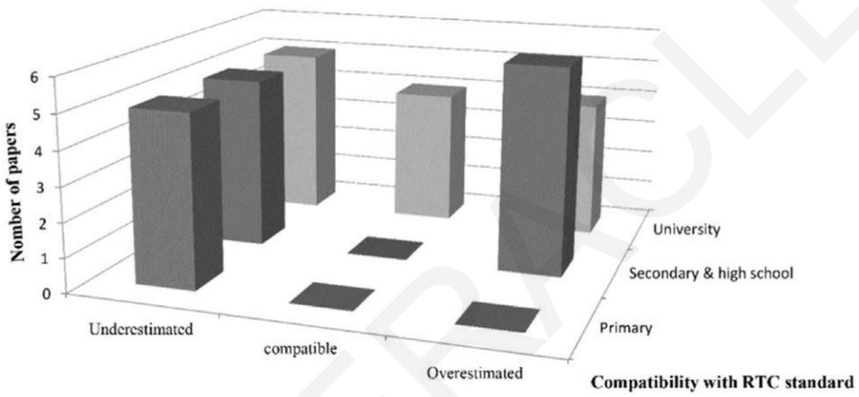



Figure 3.11. Compatibility of the rational (RTC) model with the actual thermal sensation in different educational levels [139].

Fanger and Toftum [83], Singh et al. [165] and Yao et al. [166], realising the difference in the expectations between people who are not used to occupying air-conditioned environments and those who are. Therefore, given the behavioural, physiological and psychological adaptations, they eventually proposed the adaptive PMV ("aPMV"), the extended PMV ("Epmv") and the corrected PMV ("cPMV") indexes to widen the use of PMV even in non-air-conditioned environments, by means of an expectancy factor and an adaptive coefficient. These indexes show a good agreement between predicted and subjective votes.

Among studies that used the adaptive model, 33% reported lower neutral and comfort levels in comparison to standards, and 43% reported higher neutral temperatures, although 24% compatibility was observed with the adaptive standards, especially at the university level (Figure 3.12). In addition, results reveal that the adaptive method predicts more accurately the comfort levels in the tropical/megathermal climates (Figure 3.11) [165]. Rijal et al. [167] and Humphrey et al. [135] are working to further inform the adaptive quality in the relationship of climate and comfort in indoor spaces and extend the database of thermal comfort. Specifically, they have developed the aforementioned Griffiths' method which can estimate the modified thermal comfort temperature based on the modified thermal sensation of the subject.

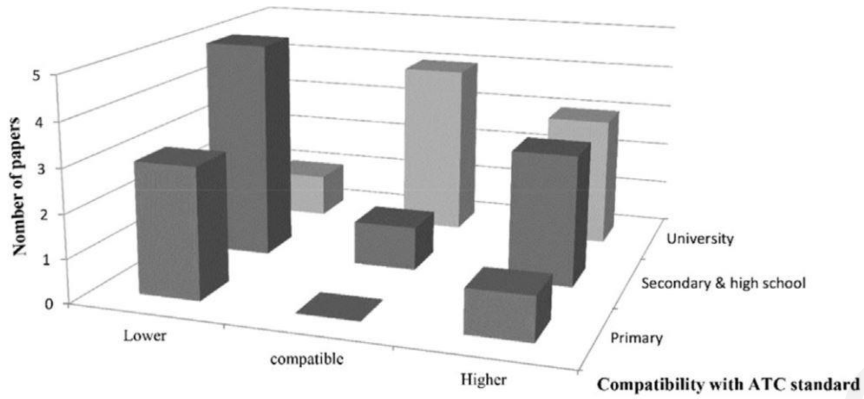



Figure 3.12. Compatibility of the adaptive (ATC) model at different educational levels [139].

### *3.6.3. Previous studies about thermal comfort in educational buildings*

Several studies were conducted on thermal comfort in educational buildings. In 2015, de Dear et al. [168] reviewed fourteen existing field studies on comfort in school classrooms. This work was subsequently complemented by a comprehensive review by Zomorodian, Tahsildoost, and Hafez [139] that covered 48 papers on thermal comfort field studies in classrooms published from 1969 to 2015, covering aspects such as different climates, ventilation types, and time of year. The authors show that most of the studies focus on naturally ventilated classrooms and that ventilation is an essential determinant of indoor air quality, thermal comfort and energy saving. The majority of studies concluded that students' thermal preferences were outside the comfort range provided by the standards.

In a recent review article by Zomorodian et al. [139], the studies are classified into three groups, i.e., the primary level (students 7-11 years of age), the secondary/high school level (12-17 years of age), and the university level (18-28 years of age). According to this paper, thermal comfort investigations in classrooms have mostly been performed at the university level, followed by secondary/high schools, whereas studies on primary schools constitute the lowest number and have mainly been performed in Europe. Moreover, Zomorodian et al. have grouped the field studies by the Köppen-Geiger climate classification. Data reveals that most of the studies (65%) are conducted in group C of that classification, temperate/mesothermal climates, including the UK [116], [169]–[171], USA [172], China [164], [166], [173], [174], Italy [161], [163], [175]–[177], Netherlands [26], [158], India [178], South Korea [179], Japan [180], Taiwan [181]–[184], Portugal [185] and Greece [186]. Figure 3.13 illustrates a particular finding of Zomorodian et al., specifically the neutral temperatures and the lower and upper acceptable limits at all educational stages. A narrower range of comfort bandwidth is traced for children in primary schools compared to students in secondary/high school and university classrooms.

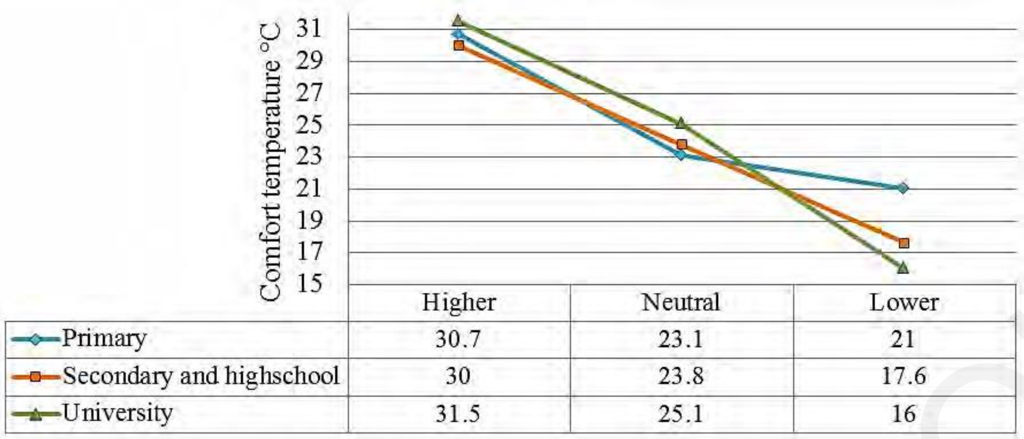



Figure 3.13. The comfort temperature limits at different educational stages [139].

Some studies on educational buildings in Southern Europe, that are mostly free-running buildings, reveal a variation in the performance of those buildings. Specifically, De Giuli et al. [159] examined the indoor environment quality of seven schools in Italy using spot measurements and questionnaires. They found that, during the summer, students are not satisfied with the indoor conditions due to high indoor temperatures. Moreover, Duarte et al. [187] assessed the thermal comfort of a Portuguese secondary school and the effect of window opening patterns using an experimental study for two years and the results suggest that classrooms were thermally comfortable despite low outdoor conditions during the winter period while, during summertime, no overheating was exhibited. In addition, the passive strategy of ventilation was be used when the outdoor temperature exceeded 16°C providing indoor air quality and thermal comfort. Dorizas et al. [188] investigated the indoor thermal comfort in nine primary schools in Greece during the spring period using the PMV and the PPD. The study reveals that the majority of students were at a warm environment by the 7-point scale of thermal sensation, and preferred a cooler environment. However, the majority stated that the indoor conditions were acceptable. In the study of Giuli, Pos and Carli [159], 7 Italian schools were evaluated for their comfort performance. Temperature, humidity, illuminance and $CO_2$ concentration were recorded and combined with field questionnaires. Results revealed that pupils complained mostly about the thermal conditions during the warm seasons, as well as about poor indoor air quality and noise. In another study [163], the authors proposed an expectancy factor of the PMV for the Mediterranean climate. This value was the result of a combined subjective and objective investigation of about 200 Italian classrooms and more than 4000 students, during both winter and summer. All the investigated school buildings were non-air conditioned and ventilated by operable windows. The results show a good agreement between predicted and subjective votes attributed to the environment. An expectancy factor was developed in order to correct the difference in the expectations between people which were not used to air-conditioned environments and naturally ventilated environments. Furthermore, Papazoglou et al. [189] evaluated a free-running secondary school in Athens during winter using the PMV and PPD indexes for both questionnaires and in-situ monitoring and reached to the conclusion that the results underestimated the mean vote, estimating a cooler sensation than the one occurred. In a similar framework, Katafygiotou and Serghides [190] assessed the thermal comfort of a secondary school in Limassol, Cyprus, using the PMV and PPD indexes for both the monitored indoor air temperatures and questionnaires. The study reveals that indoor environment conditions are mostly unsatisfactory for the occupants as the majority feels discomfort.

Some other studies conducted in other climates discuss the relationship between indoor temperatures and thermal comfort. Specifically, Auliciems [170], [191] concluded that the temperature for optimum thermal comfort in classrooms in the UK is between approximately 15°C to 21°C, while the neutral temperature is 17.1°C. Another study undertaken in schools in the UK investigated the relationship between indoor temperature and clothing insulation indicating different comfort temperatures for different clothing, i.e. 24.5°C and 21.5°C for light and heavy clothing respectively [33]. Ter Mors et al. [158] focused on the actual thermal sensitivity and clothing insulation of children in non-air-conditioned classrooms in the Netherlands, by means of both physical measurements and questionnaires. The study shows that children prefer lower temperatures than the ones predicted by a PMV model, confirming the theory of adaptive comfort in non-air-conditioned spaces [80]. Baruah et al. [178] investigated the thermal comfort temperatures in classrooms in India and concluded that the comfort zone varies from 22°C to 23.5°C in heating periods and 27.3°C to 30.7°C in cooling periods. Students physiologically and psychologically responded to the environment by adjusting their clothing, by using fans and closing or opening windows. De Dear et al. [168] surveyed the thermal comfort of students at primary schools in Australia and found that classrooms with a neutral working temperature were the optimum in terms of students' performance. On the other hand, Shahzad et al. [192] question whether neutral thermal sensation is identical to thermal comfort. Based on their study in Norwegian and British offices, 36% of responders did not want to feel neutral while, they felt comfortable in thermal sensations other than neutral. The study concludes that thermal sensation, in combination with thermal preference, could give more accurate results for the thermal comfort of occupants.

Singh et al. [27], who researched the development in thermal comfort studies in classrooms over the last 50 years, found that the studies on thermal comfort in educational buildings are scarce compared to the broader academic field of thermal comfort studies. Although there is a growing concern about students' performance and well-being, the gap between students' performance and indoor environmental quality is still valid. According to the study, the growing number of studies in the field increases the chances of covering the majority of issues related to thermal comfort, overcoming the limitations, and giving valuable knowledge about drawing correct conclusions on the best way to design or give feedback related to buildings designed for teaching and learning, to behaviour, clothing and furnishing infrastructure in classroom practices.

### *3.6.4. Previous studies about the impact of natural ventilation on thermal comfort and energy performance*

Ventilation levels in schools affect thermal comfort, indoor air quality and health, and in a more indirect manner, the learning capacity and performance of students [39]. Inadequate ventilation in schools has been found to be associated with the sick building syndrome, increased complaints by students and increasing absenteeism [193], [194].

Classrooms often provide unsuitably high temperatures, even in cold countries. The most common reasons for such high temperatures are low classroom ventilation rates which are unable to remove the heat load caused by the occupants, and the radiation heat due to sunlight entering through the windows [195].

A series of research studies highlight that natural ventilation is an important cooling strategy for the Mediterranean region as well as for other hot climates [196]–[200]. Designing a naturally ventilated building is considered a challenging task as there are several factors affecting its performance. Several diverse design elements influence the performance of natural ventilation including window to floor ratio, the way the space is ventilated (for example by single-sided ventilation or cross-ventilation), window opening patterns and others. According to Fung and Lee [201], ventilation mode hasthe most significant effect on the ventilation rate. Natural ventilation is beneficial when the outdoor temperature is within the thermal comfort zone. Moreover, natural ventilation during night-time can enhance the indoor environmental conditions during the next day [202].

Classrooms in southern European countries are traditionally naturally ventilated [51]. During the intermediate seasons, windows are open and occupants welcome the fresh outdoor airflow into the classrooms.  In warmer periods, the risk of overheating increases; nevertheless, the risk is reduced with properly-sized windows, appropriate solar protection, night-time ventilation and the use of building mass [187].

The positive impact of natural ventilation for improved thermal comfort and indoor air quality, as well as energy saving, is highlighted in several studies. Harvey [203]  has aptly demonstrated the great potential of natural ventilation in energy saving and in maintaining occupant satisfaction levels high, especially in southern European areas. It was found that naturally ventilated buildings consume 30-40% less energy compared to hybrid mechanically ventilated buildings [204]–[207].  The research of Becker et al. 2007 [58] indicates that applying improved ventilation schemes in an otherwise well-designed energy-conscious building results in saving 28-30% energy in northern and 17-18% in southern classroom orientations, respectively. In another studies [195], the authors confirm that primary energy saving by means of natural ventilation lies within the range of 18-33% while maintaining classroom comfort levels. These findings demonstrate significant reduction of the energy consumption required for technical cooling, highlighting that natural ventilation is a suitable passive strategy during the cooling period. Moreover, the ability of night ventilation to reduce energy consumption in buildings and improve thermal comfort was demonstrated in an extensive study of 214 residential buildings in Greece. More specifically, the findings show that night ventilation decreased the cooling loads of buildings by approximately 40 kWh/$m^2$ [208].

According to Givoni [73], daytime ventilation is most appropriate for mild climates, where the air temperature and humidity of the external environment fall within comfort limits. More specifically, daytime ventilation is recommended for cooling purposes when the maximum air temperature of the external environment varies between 28°C and 32°C and the indoor wind speed from 1.5 to 2 m/s. According to the same source, daytime ventilation is beneficial when diurnal temperature fluctuation is less than 10°C. By contrast, night ventilation is preferable for cooling in regions where nocturnal outdoor air temperature is around 20°C and diurnal temperature fluctuation is more than 10°C.

According to Kolokotroni and Aronis [204], night ventilation is a successful passive design strategy if it improves the indoor thermal condition during the following day by reducing both peak and average air temperatures. In a similar vein, Kyritsi and Michael [209], have investigated the influence of natural ventilation on the thermal comfort of indoor office building environments in areas with Mediterranean climate. The studies have revealed that night-time cross ventilation is an efficient ventilation strategy for cooling during the summer period since it utilizes to the full, the low temperatures of the outdoor environment during night-time therefore reducing the peak indoor air temperature of the following day. In a similar context, the author [210] investigate the vulnerability of educational buildings in Cyprus, in view of future climatic conditions, by means of a dynamic simulation software and examine the impact of natural ventilation on thermal comfort. The results show that night ventilation is an effective strategy for the reduction of the risk of overheating especially in the Typical Meteorological Year (TMY). However, this strategy alone is unable to cope with future overheating predictions. Kubota et al. [211] investigated the performance of different ventilation strategies in Malaysian terraced houses (with hot-humid climate) in order to identify the most effective ventilation strategy. The results of the field experiment indicate that the cooling effect of night ventilation is greater than that of other ventilation strategies during the day and night. The effectiveness of cooling ventilation strategies is also confirmed in other studies [196], [197], [212] where the authors quantified the positive contribution of natural ventilation in a residential vernacular building of the eastern Mediterranean region. The conducted research establishes that the night ventilation strategy has a positive impact on the cooling effect of indoor spaces during the hot summer period compared to daytime and full-day (24-h) ventilation. Solgi et al. [213] have reviewed contemporary studies with regards to the key parameters and the efficiency of night ventilation, illustrating the impact of thermal energy storage on the effectiveness of night ventilation. The positive impact of natural ventilation on indoor thermal comfort is also reported in the study of Yao et al. [214] who investigated the effect of passive measures on thermal comfort and energy conservation in China. According to a study performed by Nematchoua et al. [215], who investigated the thermal comfort of hospitals and shopping centres under natural ventilation in Madagascan

Island, the most preferable passive strategy reported was opening windows in a pattern that accommodates individual needs.

The positive impact of natural ventilation on improving thermal comfort and reducing energy consumption is also presented in the studies of Spentzou et al. [216], [217], who investigated different ventilation strategies using dynamic simulation in Mediterranean dwellings in Greece. Specifically, the strategies include day and night cross ventilation, a wind-catcher and a dynamic façade that responds to environmental parameters using automatically controlled shading devices. The results highlight the beneficial impact of ventilation on thermal comfort showing that the combined operation of wind–catcher and dynamic façade can reduce the temperature up to 7°C, and can provide acceptable ventilation rates for up to 65% of the cooling period. Another study performed by Irulegi et al. [218] in office buildings in Spain showed that night ventilation eradicated the need for air conditioning during the working hours of the next day, thus demonstrating the positive effect of night ventilation on thermal comfort.

### 3.7. Chapter summary

This chapter has presented a review of the key literature on the theory of thermal comfort. It has described the differences between climate chamber studies and field studies and discussed the widely used thermal comfort approaches for the assessment of the thermal sensation and satisfaction of building occupants within indoor environments. It should be noted that these approaches have been developed mainly for adults. The chapter has reviewed the criteria of the current comfort standards for the evaluation of thermal environments, especially in naturally ventilated spaces. However, no student-centred approach is included in these standards for the assessment of the thermal condition in naturally ventilated classrooms. This chapter, by reviewing previous studies on thermal comfort in educational buildings, highlights the importance of indoor conditions on the performance of students and underlines the positive impact of natural ventilation in free-running buildings. The literature review in the context of classrooms reinforces the knowledge gap regarding thermal comfort evaluation in a free-running indoor environment with students as the long-term occupants. The information provided in this chapter forms the theoretical framework of this research as a whole, and suggests the basis for developing a new approach for the investigation of the thermal perceptions of students in secondary school classrooms.

Thermal comfort plays an important role in the quality of indoor environments and affects occupants' health, performance and productivity. As students spend the majority of their time in schools, acceptable thermal comfort is an important factor to taken in consideration. Current thermal comfort standards, e.g., ASHRAE 55:2013, ISO 7730:2005, and EN 15251:2007, define acceptable indoor operative temperatures for the design of buildings based on the heat balance and adaptive thermal comfort models. Besides the use of comfort standards for the assessment of classroom thermal environments, many studies state that the prediction models underestimate or overestimate the actual thermal sensation; therefore, subjective survey is considered important for the validation of the results. The results of the studies conducted at the same educational level and climate zones reveal that there has been a wide disparity in the obtained thermal neutrality. This finding underlines the need for more micro-level thermal comfort studies covering different cultural and social backgrounds that influence students' expectations.

Thermal comfort field surveys have been mostly performed with a limited number of respondents during distinct seasons. Enlarging the sample size and seasonal field investigations throughout the school year enhances the quality of the data and develops an understanding of students' thermal perception. The outcomes from previous studies reinforce the need for further research in the field, particularly in naturally ventilated secondary schools in the east-Mediterranean region. This study conducts an extensive research to contribute to the understanding of the thermal comfort conditions of educational buildings in Cyprus and of the actual thermal perception of students with the aim of improving thermal comfort in classrooms.

# Chapter 4. A review of the literature about air quality

## 4.1. Introduction

The purpose of this chapter is to develop a conceptual framework and build a theoretical basis for defining the meaning of air quality based on the available literature. This chapter reviews the basic principles of air quality and provides a context for the investigation of the relationship between the indoor environment and the air quality of students in naturally ventilated buildings. To achieve the general purpose of the chapter, firstly the definition of the meaning of air quality is provided associated with the parameters that affect the air quality. Secondly, the study explores the existing approaches to the evaluation of air quality that are widely used in academic researches while reviewing the inclusion of these approaches in international and European standards. Following, there is a brief evaluation of the previous studies related to the impact of air quality on the performance of students, to air quality in indoor spaces in general and to the impact of natural ventilation on air quality. Finally, a chapter summary is provided.

## 4.2. Defining the meaning of air quality

The scientific interest in the air quality of indoor building environments over the past few decades has been linked to the recognition of indoor pollution as an important factor for the health of users within the building envelope. A large proportion of people's time, reaching even 90%, is spent indoors; either in school or college premises, in commercial or industrial buildings or inside their residing places [219]. The quality of the indoor built environment and thus the health and productivity of users is highly affected by indoor air quality and thermal comfort conditions. The European Environmental Agency suggests that the concentration of pollutants in the indoor environment is much higher than that of the urban outdoor ambient environment with average traffic [219]. However, indoor air quality has received less attention than that of the outdoor air quality, especially up until the last decade. Poor indoor air quality can be especially harmful to vulnerable groups such as children, elderly and those with cardiovascular and chronic respiratory diseases. Apart from its profound effect on health, indoor air pollution reduces the comfort and productivity of occupants of the building. In several researches a statistically significant partial correlation was reported between headache, dizziness, heavy head, tiredness, difficulties concentrating, unpleasant odour, and high $CO_2$ concentrations [39].

According to the American Society of Heating, Refrigerating and Air Conditioning Engineers (known as ASHRAE), the **acceptable Indoor Air Quality** (IAQ) is: "Air in which there are no known contaminants at harmful concentrations, as determined by cognizant authorities, and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction" [220].

All the above only confirm that the amount of time spent in school premises affects school indoor environmental quality (IEQ). Children are more sensitive to the unpropitious effect of indoor pollutants caused by poor air quality in schools [221]. According to Zhao et al. [222], various pollutants such as bacteria, mould, volatile organic compounds (VOCs), allergens, and particulate matter (PM) can decrease indoor air quality (IAQ) in classrooms. VOCs can be emitted from materials used during the building construction or operation [223], mould and bacteria may grow due to dampness and moisture damage [224], while allergens and particulate matter (PM) may be brought into school by ventilation or students and staff. Interaction between these compounds can also alter IAQ [225]. In the following tables, the main indoor pollutants and their sources in educational buildings are presented.

Table 4.1. Main indoor pollutants and their sources in educational buildings

| **Human activity** | |
|---|---|
| **Sources** | **Pollutants** |
| Users | Carbon Monoxide (CO), Carbon Dioxide ($CO_2$) |
| Clothing | Bacteria, Fungi |
| Perfume | Toxic Matter |
| Cigarette's smoke | Carbon Monoxide (CO), Formaldehyde, $NO_x$, Benzene, Hydrazine |

| **Main classrooms** | |
|---|---|
| **Sources** | **Pollutants** |
| Markers | VOCs, Organic solvents |
| Chalk | Particulate Matter $PM_{10}$ |
| Floors | Formaldehyde, Toluene, Xyline, Styrene, Bacteria |
| Synthetic floor | Phenol, Formaldehyde |
| Carpet | Toxic Matter, Bacteria |
| Ceilings | Microbial growth, Bacteria, Fungi |
| Insulation materials | Fibers, VOCs |

| **Special use spaces** | |
|---|---|
| **Sources** | **Pollutants** |
| Workshops | VOCs |
| Painting workshops | Toxic Matter |
| Vestiary | Toxic Matter, Bacteria, Viruses |
| Sanitary facilities | Bacteria, Lead, Appearance of viruses |

| **Technical equipment** | |
|---|---|
| **Sources** | **Pollutants** |
| Air duct system | Microbial growth, Viruses |
| Computer | Ozone, VOCs, Phosphoric Acid |
| Photocopier | VOCs, Ozone, NO, Graphite Particles, Ammonia, Acetic Acid |
| Laser printer | Aldehydes, Styrene, Hydrocarbons, Ozone, Formaldehyde, Graphite |
| Canteen equipment | Carbon Monoxide (CO), Sulfur dioxide ($SO_2$), Nitrogen Dioxide ($NO_2$), Bacteria, Fungi |

| **Fixed equipment- Furniture** | |
|---|---|
| **Sources** | **Pollutants** |
| Partitions | Formaldehyde, Toluene, Benzene, Bacteria |
| Bearings. Furniture | Formaldehyde, VOCs, Toxic Matter, Heavy metals |
| Curtains | Formaldehyde, Aldehydes |

## 4.3. International standards for air quality

Due to the possible health effects that may be caused by the unsatisfactory quality of indoor air, the need to take substantial efforts and immediate measures arises to limit human exposure to environmental pollutants. In this regard, the international scientific community has focused its efforts on formulating and proposing general guidelines, advice and standards for improving the quality of indoor air and states in enacting relevant legislation. Air quality regulations and guidelines set limits for both the minimum allowable concentration of a large number of pollutants and the minimum level of ventilation in air change per hour.

The United States has made great progress with the Clean Air Act and Air Pollution since 1970, with the 1990 Amendments which were a milestone in the Clean Air Act history , signed on November 15, 1990. These amendments set the stage for protecting the ozone layer, reducing acid rain and toxic pollutants, and improving air quality and visibility. The Clean Air Act requires the EPA (United States Environmental Protection Agency) to set National Ambient Air Quality Standards (NAAQS) for pollutants that are common in outdoor air and are considered harmful to public health and the environment which come from numerous and diverse sources. The statute established two types of national air quality standards: primary standards and secondary standards. Primary standards provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings [226].

The EPA has set the National Ambient Air Quality Standards for six principal pollutants, which are called "criteria" air pollutants. Periodically, the standards are reviewed and may be revised. The current standards are adopted by the ASHRAE 62.1-2019. Units of measure for the standards are parts per million (ppm) by volume, parts per billion (ppb) by volume, and micrograms per cubic meter of air ($\mu g/m^3$) [227].

The World Health Organization (WHO) which operates on an international level, also offers guidelines to policy-makers on reducing the effects on health of air pollution. The first edition of the WHO Air quality guidelines for Europe was published in 1987, and since then scientific knowledge about the effects of exposure to air pollution and the magnitude of its public health impact has increased exponentially. The first edition summarized scientific knowledge on the health hazards related to the 28 most common air pollutants, providing a uniform basis for risk assessment for national authorities responsible for protecting populations from the adverse effects of air pollution. In the early 1990s, the growing body of knowledge allowed WHO to initiate a process for revising the guidelines and eventually publish them in 2000, summarizing risk characterization of 37 pollutants. Since the publication of the second edition there has been an increasing awareness among scientists and policy-makers of the global nature and magnitude of the public health problems posed by exposure to air pollution, based on hundreds of new studies published in scientific literature. The project "Systematic review of health aspects of air pollution in Europe", carried out by the WHO Regional Office for Europe to support the development of the European Union's Clean Air for Europe (CAFE) programme in 2002–2004, concluded that this new evidence warranted revision of the air quality guidelines for particulate matter (PM), ozone and nitrogen dioxide. Of particular importance in deciding that the guidelines should apply worldwide, was the substantial and growing evidence of the health effects of air pollution in the low- and middle-income countries of Asia, where air pollution levels are the highest. WHO's comparative risk assessment quantified the burden of disease due to air pollution worldwide and, as noted above, found the largest burden in the developing countries of Asia [228]. The WHO guidelines are adopted by the European Standard EN 13779:2007 (replaced by EN 16798-3:2017).

If there is no concern of specific health complaints or single pollutants, sufficient indoor air quality is mainly based on indirect approaches, such as ventilation rates. Different standards, including the ASHRAE Standard 62 [220] and the CEN EN 15251:2007 [87] provide minimum ventilation rates for different building types with the goals of improving indoor air quality via fresh air and preventing adverse health effects. Overall, there is an agreement that guidelines should consider occupant-generated contaminants, odours and emissions from buildings and furnishings. The required ventilation rates can also be calculated based on a mass balance equation using carbon dioxide ($CO_2$) as an indicator [229]. The indoor $CO_2$ level is one commonly used approach which has been referred to as an IAQ indicator for inefficient and ill-functioning air-filtration.

There are two well-known standards that are widely used for the assessment of air quality in the indoor environment:

- The EN ISO Standard 13779:2007, Ventilation for non-residential buildings — Performance requirements for ventilation and room-conditioning systems [229].

  It was replaced by EN 16798:3-2017 Energy performance of buildings, Ventilation for buildings. For non-residential buildings. Performance requirements for ventilation and room-conditioning systems (Modules M5-1, M5-4) [230] and EN 16798-1:2019 Energy performance of buildings- ventilation for buildings – Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics Module M1-M6 [118].

- The ANSI/ ASHRAE Standard 62.1-2019, Ventilation for Acceptable Indoor Air Quality [220].

In addition, there are other guidelines dealing with the values of indoor air quality such as the:

- Representatives of European Heating and Ventilation Associations (REHVA) Guidebook No.13. Indoor environment and energy efficiency in schools, 2010 [231]
- Building Bulletin 101 Ventilation, thermal comfort and indoor air quality, 2018 [232].

### *4.3.1. European Standards*

*EN 13779:2007*

Regarding the outdoor air quality, Table 4.2 shows the key pollutants taken into account for the classification of the outdoor air quality. The outdoor air classification is given in Table 4.3 and the indoor air quality classification, with the classification by $CO_2$-level is provided in Table 4.4.

Table 4.2. Key air pollutants [229].

| **Pollutant** | **Average time** | **Guideline value ($\mu g/m^3$)** | **Source** |
|---|---|---|---|
| **Sulphur dioxide $SO_2$** | 24 hrs | 125 | WHO 1999 |
| | 1 year | 50 | WHO 1999 |
| **Ozone $O_3$** | 8 hrs | 120 | WHO 1999 |
| **Nitrogen dioxide $NO_2$** | 1 year | 40 | WHO 1999 |
| | 1 hrs | 200 | WHO 1999 |
| **Particulate Matter $PM_{10}$** | 24 hrs | 50<br>Max. 35 days exceeding | 99/30/EC |
| | 1 year | 40 | 99/30/EC |

Table 4.3. Classification of outdoor air (ODA) [229].

| **Category** | **Description** | **Explanation** |
|---|---|---|
| **ODA 1** | Pure air which may be only temporarily dusty (e.g. pollen) | ODA 1 applies where the WHO (1999) guidelines and any National air quality standards or regulations for outdoor air are fulfilled. |
| **ODA 2** | Outdoor air with high concentrations of particulate matter and/or gaseous pollutants | ODA 2 applies where pollutant concentrations exceed the WHO guidelines or any National air quality standards or regulations for outdoor air by a factor of up to 1.5. |
| **ODA 3** | Outdoor air with very high concentrations of gaseous pollutants and/or particulate | ODA 3 applies where pollutant concentrations exceed the WHO guidelines or any National air quality standards or regulations for outdoor air by a factor of greater than 1.5. |

Table 4.4. Basic classification of indoor air quality and $CO_2$ level in rooms [229].

| **Category** | **Description** | **$CO_2$ level above level of the outdoor air in ppm** | |
|---|---|---|---|
| | | Typical range | Default value |
| **IDA 1** | High indoor air quality | ≤ 400 | 350 |
| **IDA 2** | Medium indoor air quality | 400 - 600 | 500 |
| **IDA 3** | Moderate indoor air quality | 600-1000 | 800 |
| **IDA 4** | Low indoor air quality | >1000 | 1200 |

*EN 16798-1:2019*

In the revised version of EN 13779:2007, i.e. EN 16798-1:2019, a total minimum airflow rate during occupancy is expressed in l/s per person and specifically 4 l/s per person in order to maintain health. Table 4.5 shows the ventilation rates for sedentary adults, not-adopted persons for diluting emissions from people for different categories. Table 4.6 shows the revised default design $CO_2$ concentrations above outdoor concentrations assuming a standard $CO_2$ emission of 20 L / h per person.

Table 4.5. Design ventilation rates for adults, non-adapted persons for diluting emissions from people for different categories [118].

| Category | Level of expectation | Expected percentage dissatisfied | Airflow per non-adopted person (l/s per person) |
|---|---|---|---|
| **I** | High | 15 | 10 |
| **II** | Medium | 20 | 7 |
| **III** | Moderate | 30 | 4 |
| **IV** | Low | 40 | 2.5 |

Table 4.6. Default design $CO_2$ concentration above outdoor concentration assuming standard $CO_2$ emission of 20 l/(h per person) [118].

| Category | Corresponding $CO_2$ concentration above outdoors in ppm for non-adapted persons |
|---|---|
| **I** | 550 |
| **II** | 800 |
| **III** | 1350 |
| **IV** | 1350 |

In the revised version of EN 13779:2007, the standard gives revised suggested guideline values for indoor and outdoor air pollutants as formulated by the WHO. For some pollutants no indoor air requirements have been defined yet by WHO; therefore, only WHO outdoor requirements are presented (3rd column). In case of specific indoor pollution, ventilation rates shall be adapted to optimize the diluting effect of ventilation and additional air cleaning strategies can be considered according to the standard EN 16798-1:2019.

Table 4.7. WHO guidelines values for indoor and outdoor air pollutants [118].

| Pollutant | WHO Indoor Air Quality guidelines 2010 | WHO Air Quality guidelines 2005 |
|---|---|---|
| **Benzene** | No safe level can be determined | - |
| **Carbon monoxide** | 15 min. mean: 100 mg/m$^3$<br>1 h mean: 35 mg/m$^3$<br>8 h mean: 10 mg/m$^3$<br>24 h mean: 7 mg/m$^3$ | - |
| **Formaldehyde** | 30 min. mean: 100 μg/m$^3$ | - |
| **Naphthalene** | annual mean: 10 μg/m$^3$ | - |
| **Nitrogen dioxide** | 1 h mean: 200 μg/m$^3$ | - |

| | | |
|---|---|---|
| | annual mean: 20 µg/m$^3$ | |
| **Polyaromatic Hydrocarbons** | No safe level can be determined | - |
| **Radon** | 100 Bq/m3<br>(sometimes 300 mg/m$^3$<br>country-specific) | - |
| **Trichlorethylene** | No safe level can be determined | - |
| **Tetrachloroethylene** | annual mean: 250 µg/m$^3$ | - |
| **Sulfure dioxide** | - | 10 min. mean: 500 µg/m$^3$<br>24 h mean: 20 µg/m$^3$ |
| **Ozone** | - | 8 h mean: 100 µg/m$^3$ |
| **Particulate Matter PM 2.5** | - | 24 h mean: 25 µg/m$^3$<br>annual mean: 10 µg/m$^3$ |
| **Particulate Matter PM 10** | - | 24 h mean: 50 µg/m$^3$<br>annual mean: 20 µg/m$^3$ |

### *4.3.2. ASHRAE 62.1-2019*

The ASHRAE 62.1-2019 presents the national ambient air quality standards for the United States and it is shown in Table 4.5. The Clean Air Act identifies two types of national ambient air quality standards. Primary standards provide public health protection, including protecting the health of sensitive populations, such as asthmatics, children, and the elderly. Secondly standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

Table 4.8. National Air Quality Standards for the United States [220].

| **Pollutant** | | **Primary/ Secondary** | **Averaging Time** | **Level** | **Form** |
|---|---|---|---|---|---|
| **Carbon Monoxide (CO)** | | Primary | 8 hours<br>1 hour | 9 ppm<br>35 ppm | Not to be exceeded more than once per year |
| **Lead (Pb)** | | Primary and secondary | Rolling 3-month average | 0.15 µg/m$^3$ | Not to be exceeded |
| **Nitrogen Dioxide ($NO_2$)** | | Primary | 1 hour | 100 ppb | 98$^{th}$ percentile of 1 hour daily maximum concentrations, averaged over 3 years |
| | | Primary and secondary | 1 year | 53 ppb | Annual mean |
| **Ozone ($O_3$)** | | Primary and secondary | 8 hours | 0.070 ppm | Annual 4$^{th}$ highest daily maximum 8-hour concentration, averaged over 3 years |
| **Particle Pollution (PM)** | PM2.5 | Primary | 1 year | 12 µg/m$^3$ | Annual mean, averaged over 3 years |
| | | Secondary | 1 year | 15 µg/m$^3$ | Annual mean, averaged over 3 years |
| | | Primary and secondary | 24 hours | 35 µg/m$^3$ | 98$^{th}$ percentile, averaged over 3 years |

| | | | | |
|---|---|---|---|---|
| PM10 | Primary and secondary | 24 hours | 150 μg/m$^3$ | Not to be exceeded more than once per year on average over 3 years |
| **Sulphur Dioxide ($SO_2$)** | Primary | 1 hour | 75 ppb | 99$^{th}$ percentile of one-hour daily maximum concentrations, averaged over 3 years |
| | Secondary | 3 hours | 0.5 ppm | Not to be exceeded more than once per year |

ASHRAE 62 recommends a minimum ventilation rate of 8 L/s-person (15 cfm/person) for classrooms. Given typical occupant density of 33 per 90m$^2$ (1000 ft$^2$) and a ceiling height of 3m (10 ft), the current ASHRAE standard would require an air exchange rate of about 3 air changes per hour (ACH) for a classroom.

### *4.3.3. Other Guidelines*

The Representative of European Heating, Ventilation, and Air Conditioning Associations **(REHVA)** published a guidebook about the indoor environment and energy efficiency in schools as school buildings represent a significant part of the building stock and a noteworthy part of the total energy use. The aim of the guidebook is to give an overview of the keys issues of school buildings' envelopes and systems design and to provide critique on these. Eventually the purpose of the guidebook is to obtain comfortable and energy sustainable environments. Regarding indoor air quality specifically, the REHVA set an acceptable limit of 1500 ppm for the $CO_2$ concentration levels [231].

The same limit is set by the authority of the public educational buildings in the United Kingdom in the **Building Bulletin 101** [232]. The UK Air Quality Standards Regulation 2010 is aligned with the WHO guidelines of 2010 and recommendations for selected indoor air pollutants. Table 4.9 presents the WHO indoor air quality guidelines and UK ambient air quality objectives.

Table 4.9. WHO IAQ guidelines and UK ambient air quality standards [232].

| **Pollutants** | **WHO Indoor Air Quality Guidelines (2010)** | **The Air Quality Standards Regulations 2010** |
|---|---|---|
| **CO (mg/m$^3$)** | 100 (15 min) | |
| | 60 (30 min) | |
| | 30 (1 hr) | |
| | 10 (8 hr) | 10 (8 hr) |
| | 7 (24 hr) | |
| **NO2 (μg/m$^3$)** | 200 (1hr) | 200 (1 hr) not to be exceeded more than 18 times a calendar year |
| | 40 (1yr) | 40 (1yr) |

| | | |
|---|---|---|
| | | 350 (1 hr) not to be exceeded more than 24 times a calendar year |
| | | 125 (24 hr) not to be exceeded more than 3 times a year |
| **$PM_{10}$ (µg/m$^3$)** | | 50 (24 hr) not to be exceeded more than 35 times a calendar year |
| | | 40 (1 yr) |
| **$PM_{2.5}$ (µg/m$^3$)** | | 25 (1 yr) |
| **Ozone (µg/m$^3$)** | | 125 (8 hr) not to be exceeded on more than 25 days per calendar year averaged over three years |
| **Radon (Bq/m$^3$)** | No safe level | From Ionising Radiations Regulations not AQSR: 400 (approximately equal to annual average of 270) |
| | Reference level: 100 | |
| | No more than: 300 | |
| **Benzene (µg/m$^3$)** | No safe level | |
| | | 5 (1 yr) |
| **Trichloroethylene (µg/m$^3$)** | No safe level | |
| **Tetrachloroethylene (µg/m$^3$)** | 250 (1yr) | |
| **Formaldehyde (µg/m$^3$)** | 100 (30 min) | |
| **Naphthalene (µg/m$^3$)** | 10 (1yr) | |
| **PAHs (ng/m$^3$ B[a]P)** | No safe level | 1 (total content in the $PM_{10}$ fraction averaged over a calendar year) |
| **Arsenic (ng/m$^3$)** | | 6 (total content in the $PM_{10}$ fraction averaged over a calendar year) |
| **Cadmium (ng/m$^3$)** | | 5 (total content in the $PM_{10}$ fraction averaged over a calendar year) |
| **Nickel (ng/m$^3$)** | | 20 (total content in the $PM_{10}$ fraction averaged over a calendar year) |

**Notes:**
1yr: annual mean, 24hr: 24 hour mean, 1hr: 1 hour mean, 30 min: 30 minute mean
Conversion to ppm at 25 ºC and 1 atmosphere: X ppm = (Y mg/m$^3$)(24.45)/(molecular weight)

In general, teaching and learning spaces where natural ventilation is used or when hybrid systems are operating in natural mode the following standards apply:

- sufficient outdoor air should be provided to achieve a daily average concentration of $CO_2$ of less than 1500 ppm, during the occupied period, when the number of room occupants is equal to, or less than the design occupancy.

- the maximum concentration should also not exceed 2000 ppm for more than 20 consecutive minutes each day, when the number of room occupants is equal to, or less than the design occupancy.

The minimum ventilation rate in teaching spaces proposed by the Building Bulletin 101 is 2.3 $l/s/m^2$ or 8 l/s/person whichever is the greater, when occupied. The lowest ventilation rate of 8 l/s/person for schools is also proposed by the results of the HealthVent project. The project also recommended the "health-based reference minimum ventilation rate" of 4 l/s/person, when WHO indoor air quality (IAQ) guidelines are fully respected and the only pollutants are human bio-effluents ($CO_2$). Therefore, in reality, where the WHO guidelines are not met, rates higher than 4 l/s/person are needed, but after source control measures are implemented [232].

The ad hoc working group of the Indoor Air Hygiene Commission of **German** and the Working Group of the Supreme Health Authorities of the Federal States (IRK/AOLG ad hoc working group) has produced an evaluation for carbon dioxide in indoor air. According to this, they use values as "ventilation traffic light" having green when $CO_2$ concentration is below 1000 ppm, yellow when it is 1000 - 2000 ppm and red is when it is above 2000 ppm. If a $CO_2$ value of 1000 ppm is exceeded the room should be aired, and if 2000 ppm is exceeded it must be aired. In both cases the aim should be to remain below 1000 ppm. Until 2005, a $CO_2$ value of 1500 ppm in accordance with DIN 1946 Part 2 applied as the guideline hygiene value in Germany in schools with air-conditioning installations. In July 2005 DIN 1946-2 was replaced by EN 13779, which was amended in September 2007. This EN contains recommendations for planning and installing air-conditioning systems in all non-residential buildings intended for human occupation. Indoor air is subdivided into four quality levels (Indoor Air 1 to 4). Different ventilation rates per person or per $m^2$ floor area are derived from these quality levels (Table 4.10). In 2018, the EN 13779:2007 was replaced by EN 16798 as presented above. The categorization of EN 13779:2007 and EN 16798-1:2019 is the same.

Table 4.10. Classification of indoor air quality in accordance with DIN EN 13779: 2007-09.

| **Category** | **Description** | **Increase in $CO_2$ concentration above outside air (ppm)** | **Absolute $CO_2$ concentration in indoor air (ppm)** | **Ventilation rate/outside air flow volume (l/s/person) [($m^3$/h/person)]** |
|---|---|---|---|---|
| **IDA 1** | High indoor air quality | ≤ 400 | 350 | >15 [>54] |
| **IDA 2** | Medium indoor air quality | 400 - 600 | 500 | >10-15 [>36-54] |
| **IDA 3** | Moderate indoor air quality | 600-1000 | 800 | >6-10 [>22-36] |
| **IDA 4** | Low indoor air quality | >1000 | 1200 | <6 [<22] |

## 4.4. Previous studies about air quality

### *4.4.1. Previous studies about the impact of air quality on the health and performance of students*

It seems clear that the amount of time spent in school premises affects school indoor environmental quality (IEQ) which, in turn, influences students' health, attitude and performance. Children are more sensitive to the unpropitious effect of indoor pollutants caused by poor air quality in schools [232]. The operation and maintenance of educational buildings often suffers from a lack of proper care, leading to the persistence of environmental problems in educational buildings. Consequently, the need for retrofitting of schools arises in order to ensure adequate conditions for users to fulfil their activities.

According to a study performed by Krewski et al. [233] long-term exposure to $PM_{2.5}$ is associated with decrease in average life-expectancy from 8.5 to 20 months and rise in the long-term risk of cardiopulmonary mortality by 6-13% per 10 μg/m$^3$ of $PM_{2.5}$.

Effects of $CO_2$ on human health range from physiologic (e.g., ventilatory stimulation) to toxic (e.g., cardiac arrhythmias and seizures) and anaesthetic (significantly depressed CNS activity) to lethal (severe acidosis and anoxia) [234]. Prior research has documented direct human health effects of $CO_2$ at concentrations much higher than those found in normal indoor settings [235]. Signs of asphyxia are evident when the reported atmospheric adverse impact of $CO_2$ concentration between $O_2$ is $\leq$ 16% [236]. Wargocki and Wyon [237] carried out a study in 5 primary schools and concluded that the performance of students deteriorates by 30% in conditions of high $CO_2$ concentration and high temperatures. Nematchoua et al. [215] also examined the impact of indoor environmental quality on the self-estimated performance of office workers in the tropical wet and hot climate of Cameroon, indicating that the intensity of fatigue and headache is one of the consequences of air temperature over the comfort zone. According to a study performed by Kajtar et al. [238], human well-being as well as the capacity to concentrate attention are declining when subjects spend 2 to 3 hours in a closed space with 3000 ppm or higher $CO_2$ concentration in the air. In a controlled research study in USA, Satish et al. [239] have reported that at 1000 ppm $CO_2$, decision-making performance was significantly diminished on six of nine metrics compared to the 600 ppm concentration. When the concentration was increased to 3000 ppm $CO_2$, decision-making performance was further reduced to seven of nine metrics of performance, with percentile ranks for some performance metrics decreasing to levels associated with marginal or dysfunctional performance. This indicates that direct adverse effects of $CO_2$ on human decision-making performance may be economically important. Shendell et al. [240] found student absence decreased by 10-20% when the $CO_2$ concentration decreased by 1000 ppm in 434 American classrooms. A study by Gaihre et al. [241] in Scottish schools showed that an increase of 100 ppm of $CO_2$ corresponded to a 0.2% increase in absence rates.

Human performance and comfort in indoor spaces in relation to environmental attributes have gone as far as producing a well-known phenomenon in the construction industry sector as well as in the health sector known as Sick Building Syndrome (SBS). Sick Building Syndrome is a group of health problems that are caused by the indoor environment. Uncomfortable temperature and humidity, chemical and biological pollution, physical condition, and psycho- social status are some of the factors identified as root causes of SBS [242], [243]. Symptoms experienced by people with SBS include irritation of the eyes, nose, and throat, headache, cough, wheezing, cognitive disturbances, depression, light sensitivity, gastrointestinal distress and other flu-like symptoms [244], [245]. Based on a research conducted by United States Environmental Protection Agency (US EPA) [246], the SBS symptoms are 30-200% more frequent in mechanically ventilated buildings. This is also in line with the study of Preziosi et al. [247] and Wargocki et al. [248], who state that hospital visits due to SBS are higher for occupants of mechanically ventilated and air conditioned buildings compared to occupants of naturally ventilated buildings.

On the other hand, VOCs can cause either non-carcinogenic effects or carcinogenic. The carcinogenic effects of VOCs are primarily visible in lung, blood, liver, kidney and biliary tract. The International Agency for Research on Cancer (IARC) has classified benzene as a Group 1 human carcinogen, while other VOCs such as tetrachloroethylene and ethyl- benzene are considered as probable carcinogens for humans [249]. Additionally, some VOCs may be associated with the symptoms of asthma, different allergic reactions, mucous membrane irritation and diseases of the central nervous system symptoms [250].

### *4.4.2. Previous studies about air quality in indoor spaces*

Although not the most important contaminant from a health perspective, in classrooms, $CO_2$ is the most used indicator of the ventilation efficiency, since it is a product of respiration and school buildings typically maintain high levels of occupancy during long periods of the day. Hence, $CO_2$ concentration is currently adopted as a key parameter for ventilation and IAQ evaluation [251]. High concentrations of people in indoor spaces such as classrooms assosiated with low levels of ventilation leads to poor air quality.

De Giuli et al. [159] evaluated the indoor environmental conditions of 7 Italian schools. Air temperature, relative humidity, illuminance and $CO_2$ concentration were recorded and, at the same time, a field study was conducted using questionnaires. The results revealed that students complained about thermal discomfort during the warm months. During wintertime, when classroom windows were closed due to lower outdoor temperatures, students complained about poor indoor air quality. There are numerous reports on the indoor air quality in office buildings and academic buildings from different parts of the world [252]–[257].

Brennan et al. [258] investigated the $CO_2$ concentration of nine US schools and found that concentration ranged from about 400 to 5000 ppm exceeding the 1000 ppm ASHRAE limit in 74% of the rooms. Potting et al. [259] reported an epidemiological study involving 339 students in three Dutch schools (14 classrooms) where teachers reported complaint and four schools, where teachers do not reported complaints (207 controls). All schools were constructed after 1980. Classroom $CO_2$ levels in all of the schools exceeded the Dutch standard of 1200 ppm during 27–97% of the school time. One classroom had concentrations >2500 ppm $CO_2$ 73% of the time while levels were 1100 ppm in another room at the beginning of a school day.

Smedje et at. [260], [261] reported average and ranges of indoor $CO_2$ concentration for 96 classrooms in 38 Swedish schools randomly selected from a population of 130 schools and found that 61% of them had mechanical supply while the rest rely on natural ventilation. The study showed that the average $CO_2$ concentration was 990 ppm for 38 schools but above 1000 ppm for 41% of the measurements.

Based on a study performed by Salleh et al. [262] about the indoor air quality at school environment, which reviewed more than 16 papers in the field, the findings show that only two studies met the ventilation guidelines while the rest failed to meet the ventilation guidelines. Moreover, the data indicate that, most often, mechanically ventilated and unoccupied rooms meet standards for $CO_2$, whereas naturally ventilated and occupied rooms did not. When new schools were compared to old schools, measurements were relatively equal.

Dias Pereira et al. [185] examined the indoor air quality and thermal comfort in Portuguese seconady classrooms and found that the indoor contitions were not fullfied. The peak $CO_2$ concentration values overcome 3000 ppm and in some situations, even 5000 ppm. Nevertheless, looking closely to the data, it was verified that during the occupation periods, mean $CO_2$ values varied between 384-2173ppm. Still, the maximum mean values are in both cases more than the double of the recommended value – 1000 ppm. As expected, the lowest values in both classrooms were recorded during night time, during the unoccupied period.

Haverinen-Shaughnessy et al. [263] examined 104 schools in USA and found that 87 of them had a ventilation rate below recommended guidelines based on ASHRAE 62.1, resulting from closed windows and doors. The maximum $CO_2$ concentration varied between 661 and 6000 ppm with a mean value of 1779 ppm. Mydlarz et al. [264] carried out measurements in 75 classrooms of 4 schools in the UK. It was observed that 39 % of the classrooms exceeded the recommended limit of 1500 ppm, 93 % of which were old buildings.

Almeida et al. [251] assessed the IEQ of 32 classrooms in Portugal and concluded that eight schools showed maximum $CO_2$ concentrations above 3000 ppm and four schools above 4000 ppm. Regarding the average values, only two schools presented a concentration below the limit of 1250 ppm, and in six buildings, the mean value was higher than 1500 ppm whereas in two higher than 2000 ppm. The above results prove the literal and metaphorical vitality of ventilation in classrooms.

In general, $CO_2$ concentration in schools show that they do not meet the minimum requirements for ventilation rate and air quality, at least for a significant part of the time.

*4.4.3. Previous studies about the impact of natural ventilation on air quality*

Natural ventilation is not only preferred as a strategy for thermal comfort but it additionally provides better indoor air quality. Santamouris et al. [266] monitored extensively 62 classrooms in Athens and investigated the relationship between specific ventilation patterns and carbon dioxide concentrations before, during and after the teaching period. The study reveals that about 52% of the classrooms show a mean indoor $CO_2$ concentration above 1000ppm. It also shows that the ventilation rate of 8 l/s/person maintains $CO_2$ concentration equal to 1000ppm and that the indoor/outdoor temperature determines window-opening actions to be adapted. Coley and Beisteiner [267] monitored UK primary schools and concluded that opening windows between classes can reduce $CO_2$ levels and other contaminants to acceptable limits. Griffiths and Eftekhari [268] monitored a UK school during the heating period and concluded that a 10-minute purge ventilation can reduce $CO_2$ concentration by approximately 1000 ppm without compromising thermal comfort.

Daisey et al. [39] and Sundell et al. [40] reviewed studies conducted in schools and concluded that poor classroom ventilation is a cause of health symptoms. Although many studies included in this review monitored various environmental parameters in educational buildings, much fewer investigated the association with school occupant's health, and only two mentioned the interrelation between ventilation rates or $CO_2$ and health effects. Recent studies have also revealed the relationship between inadequate ventilation and learning ability [269]–[271].

Based on a study undertaken from Wargocki and Wyon [149], [272], [273], [237] when the outdoor air supply rate increased from 3.0 to 9.5 l/s per person the speed at which the children performed four numerical and two language-based tasks improved significantly, and in the case of one numerical task the percentage of errors was significantly reduced. It could be said that doubling the outdoor air supply rate would improve the performance of schoolwork in terms of speed by about 8% overall, and by 14% for the tasks that were affected significantly, with only a negligible effect on errors. A similar experiment by Petersen et al. [274] in Denmark obtained very similar results. In a field intervention study in classrooms in England [269], the time needed to solve simple mathematics tests was significantly reduced when the ventilation rate was increased from below 0.5 to 13-16 l/s per person.

Milton et al. [275] investigated the risk of sick leave associated with outdoor air supply rate in offices in the USA and found that the risk of short-term sick leave associated with respiratory diseases caused by infection was higher with an outdoor air supply rate of 12 l/s per person compared to other offices ventilated with 24 l/s per person.

The importance of ventilation in indoor air quality and the contribution to the wellbeing of students is also evidenced in the study of Trompetter et al. [276] who investigated air quality inside and outside two low decile primary school classrooms in Palmerston, New Zealand. The one classroom was fitted with a solar air heated ventilation unit. The results have shown significantly higher $PM_{10}$

concentrations within both classrooms during school hours, but the ventilated treatment classroom had, on average, 66% lower $PM_{10}$ concentrations than those measured in the unventilated control classroom. Another study performed in 162 classrooms in California by Mendell et al. [277] showed that sickness absence decreased by as much as 1.6% for each additional 1 l/s per person of ventilation rate while Fisk [278] predict a 10% reduction in illness leave when the outdoor air supply rate is doubled.

Previous studies conducted in Southern European countries, where educational buildings mostly rely on natural ventilation, reveal that manual window-airing provides improved indoor air quality and thermal comfort. Specifically, four free-running classrooms with openings along both sides of the room of a Portuguese public secondary school were monitored during two full academic years by Duarte et al. [187]. The results indicated that there was efficient natural ventilation for approximately a quarter of the academic year. This confirms the energy saving potential of the natural ventilation strategy.

Natural ventilation is therefore, deemed as an effective strategy for reducing energy consumption and improving air quality, but also as an important strategy because of its potential to be adapted to other east-Mediterranean countries as well as the fact that it can be applied to both new and refurbished buildings.

## 4.5. Chapter Summary

This chapter has presented a review of the key literature on the theory of air quality. The chapter has established the definition of air quality and reviewed the criteria given in the current standards for the evaluation of indoor air quality. This chapter reviews previous studies on air quality in educational buildings, highlighting the importance of indoor conditions on the performance of students and underling the positive impact of natural ventilation in free-running buildings. The literature review in the context of classrooms reinforces the knowledge gap regarding air quality evaluation in a free-running indoor environment with students as the long-term occupants. The information provided in this chapter forms the theoretical framework of this research as a whole and suggests the basis for developing a new approach to investigating the perceptions of students in secondary school classrooms.

Air quality plays an important role in the quality of indoor environments and affects occupants' health, performance and productivity. As students spend the majority of their time in schools, acceptable indoor air quality is an important factor to be considered. Current air quality standards, e.g., ASHRAE 62-1:2019, EN 13779:2007, and other guidelines such as REHVA and the Building Bulleting 101, clearly define such acceptable indoor air quality levels and minimum ventilation rates for the design of buildings. $CO_2$ concentration is the most used indicator and a key parameter for ventilation and IAQ evaluation. $CO_2$ concentration in many schools shows that classrooms does not meet the minimum requirements for ventilation rate and air quality, at least a significant part of the time.

Air quality field surveys have been mostly performed with a limited number of respondents in distinct seasons. Enlarging the sample size and seasonal field investigations throughout the school year enhances the quality of the data and develops an understanding of students' air quality perception. The outcomes from previous studies reinforces the need for further research in the field, particularly in naturally ventilated secondary schools in the east-Mediterranean region. This research conducts an extensive study to contribute to the understanding of the air quality conditions of educational buildings in Cyprus with the aim of improving indoor air quality in classrooms.

# Chapter 5. A review of the literature about natural lighting

## 5.1. Introduction

The purpose of this chapter is to review the literature regarding natural lighting. This chapter reviews the basic principles of daylight and provides a context for the investigation of the performance of natural lighting in educational buildings. To achieve the general purpose of the chapter, firstly the importance of daylight is provided associated with the parameters that affect the lighting performance. Secondly, the study explores the existing approaches of evaluation of lighting widely used in academic researches and describes the inclusion of these approaches in international and European standards. Moreover, a brief review of the previous studies related to the lighting performance of educational buildings is provided. Finally, a chapter summary is provided.

## 5.2. Daylighting and its importance

Before the 1940s, daylight was the primary light source in buildings [29]. In the short span of 20 years, electric lighting had transformed the workplace by meeting most or all of the occupants' lighting requirements. Recently, energy and environmental concerns have made daylighting a rediscovered aspect of building lighting design. The physics of daylighting has not changed since its original use, but building design has. Daylighting is often integrated into a building as an architectural statement and for energy savings. However, benefits from daylighting extend beyond architecture and energy. The psychological and physiological aspects of natural light should also be considered. The comforting space and connection to the environment provided to building occupants provide benefits as significant as the energy savings to building owners and managers [29].

Humans are affected both psychologically and physiologically by the different spectrums provided by the various types of light. These effects are the less quantifiable and easily overlooked benefits of daylighting. Daylighting has been associated with improved mood, enhanced morale, lower fatigue, and reduced eyestrain. One of the important psychological aspects from daylighting is meeting a need for contact with the outside living environment [279].

Natural light stimulates essential biological functions in the brain and is vital to our health. The human eye is a light-sensing system with a pupil and a photoreceptive medium called the retina which receive the different colours/spectrums of natural light. The retina contains two photoreceptors: rods and cones. Cones (which see photopic lumens or bright light) are responsible for day vision. Rods (which see scotopic lumens or dim light) are associated with night vision. Light falling on the retina and being transmitted to the hypothalamus controls our circadian rhythms [280], which are responsible for synchronizing our internal clock to 24 hours. The effects of light on circadian rhythms can be studied using physiological variables such as the daily patterns of core body temperature, levels of melatonin, urine production, cortex activity, and alertness.

Without the proper amount of light available, our circadian rhythms are affected and susceptibility to **Seasonal Affective Disorder** (SAD) is increased. SAD has been one of the most researched areas in the illnesses that are affected by light. SAD is attributed to a variety of recurring events, but has been clearly linked to the amount of light available for individuals. SAD occurrences are dependent on the availability of outdoor light in the winter and latitude. People who suffer from SAD usually report complaints every year in late fall or early winter, with symptoms that persist unrelentingly for several months. The symptoms are divided into two clinical categories: (1) melancholic, which are also common in non-seasonal depressive syndromes, and (2) atypical/vegetative, marked by sluggishness and overeating. Because the availability of outdoor light affects SAD occurrences, light can play a vital role in preventing and curing SAD.

Throughout the years, daylighting was considered to be an important factor especially in the design of schools rather than in the design of any other building [281]. Education, in its broadest sense, includes all activities designed to influence, in a particular manner, the mental and physical state of a person. Moreover, the educational process aims at providing specific knowledge, skills and abilities. Research studies in the field indicate that factors determining the physical conditions of classrooms are also of significant importance to the students' performance. More specifically, visual comfort in the indoor environment has been reported to be an important factor for learning and is recognized to enhance the educational process [30]. The positive impact of daylighting in the performance of occupants [30], [282], the creation of a pleasant environment [283], the promotion of healthier conditions [28], [283], [284] as well as the provision of energy saving [285] has been well established over the years. Without appropriate lighting levels, people cannot fulfil their daily activities effectively, efficiently and comfortably [286], [287].

Daylight has physiological and psychological benefits for teachers and students. Physiological benefits due to daylight on school children are less dental decay (cavities), improved eyesight, increased growth, and improved immune system.

The sun is a primary source of vitamin D, and increasing vitamin D intake stimulates calcium Metabolism. There is a strong correlation between the amount of sunlight a child is exposed to and the **level of dental decay**, making daylighting a very important element for cavity prevention in children. McBeath and Zuker [288]conducted a study showing children are more prone to dental cavities in the winter and spring when they spend more time inside a school and less prone during the summer months when they are outside in the sun.

Quality of light is also important for **students' eyes**. Eyes collect and convert visible light into electrical impulses called photocurrents. Daylight provides the richest spectral, usable light, and it eases some of the stress to the eye. Research shows that reading is the most visually stressful task for students [288]. Stress causes a contracted visual field in the eye that can lead to a decrease in information processing and learning ability [288].

A school with insufficient light can also reduce a **student's ability to learn** due to the effect lighting has on physiology. Poor spectral light can create strain on students' eyes, leading to a decrease in information processing and learning ability, causing higher stress levels [288]. Walker [289] found that stress impacts certain growth hormones. He determined that "persistent stress stunts bodily growth in children" because the activity of the growth-inhibiting hormones cortisol and ACTH increase under stress. According to a study performed by Hathaway et al., children under electric lights all day reduced mental capabilities, agitated physical behaviour and fatigue.

Another study performed by Ott stated that the trace amount of UV light is important to support life and maintain a healthy **immune system** [288]. Faber Birren states that this basic amount of UV light needed has been demonstrated to "intensify the enzymatic process of metabolism, increase hormone system activity, and improve the tone of the central nervous and muscular systems" [290].

Daylight also increases student and teacher **attendance.** According to a study undertaken by Bailey, in a daylit school in North Carolina, an attendance rate above 98% is shown and the teachers claimed the lowest number of faculty health absences in the area.

Daylight also helps the students in **achieving higher reading and math scores**. Based on a study performed on the North Carolina Johnston County schools, people in daylit schools had a 15% increase in test scores compared to older schools [291]. Another study performed by Heschong Mahone Group in school in California showed that the classrooms with the most amount of daylighting had a 20% faster learning rate in math and a 26% faster learning rate in reading during one school year when compared to classrooms with the least amount of daylighting. Students in classrooms with the most daylighting are progressing on the order of one to two points above the average rate in reading and math over the time span between fall and spring testing. By advancing more quickly, the Heschong Mahone Group stated that schools "could be saving up to one month of instructional time for the reading and math curriculum that could be used for other areas of learning" [292]. In addition, the study determined that the variable of daylighting had larger effects than the window variable. Therefore, the presence of natural light was responsible for the positive results of student performance, not the view from the windows. The Heschong Mahone Group also noted that daylighting is complex and its study cannot prove why daylighting causes the positive effects on students. Reasons that were cited as possible causes for the good performance from students was the better distribution of light, improved visibility from improved light, better colour rendering, and the absence of flickering from electrical lighting [292]

Moreover, according to the report issued by the International Energy Agency (IEA), artificial lighting is responsible for the consolidating amount of 14% of electricity consumption in the European Union [292][13]. Therefore, exploitation of natural lighting is an important factor for **energy consumption reduction**. Finally, the reduction of energy demands, as a result of the minimization of the use of artificial lighting, promotes **energy and environmental awareness** [293], [294]. For all the abovementioned reasons, the importance of daylight in school premises as a crucial design parameter is evidently widely acknowledged.

## 5.3. Assessment criteria of natural lighting performance

Lighting levels define the quality of visual sense. Visual comfort is defined in the European Standard EN 12665:2018 [295] as a subjective condition of visual wellbeing induced by the visual environment. Visual comfort depends on (i) the physiology of the human eye, (ii) the physical quantities describing the amount of light and its distribution in space, and (iii) the spectral emission of the light source. It has been commonly studied through the assessment of a series of factors regulating the relationship between the human needs and the light environment, such as (i) the amount of light, (ii) the uniformity of light, (iii) the quality of light in rendering colours, and (iv) the prediction of the risk of glare for occupants [295].

Common light levels outdoor at day and night can be found in the Table 5.1.

Table 5.1. Common Light Levels Outdoors from Natural Sources [38].

| **Condition** | **Illumination (lux)** |
|---|---|
| **Sunlight** | 100 000 |
| **Full daylight** | 10 000 |
| **Overcast day** | 1 000 |
| **Very dark day** | 100 |
| **Twilight** | 10 |
| **Deep twilight** | 1 |
| **Full moon** | 0.1 |
| **Quarter moon** | 0.01 |
| **Starlight** | 0.001 |
| **Overcast night** | 0.0001 |

The required lighting level in a space depends on the kind of work, duration and time of work (day or night), the users' age etc. The regulations and standards of lighting in educational buildings have differed over the years [281]. According to the current regulations and specifically the CIBSE Guide A [296], [297], IESNA [298] and European Standard EN 12464-1:2011 [299], the minimum illuminance on the working plane in educational buildings should range from 300 to 500 lux for general and special classrooms respectively and 750 lux for spaces with high lighting requirements such as drawing rooms, typing workshops etc. (Table 5.2). Another static indicator of daylight performance is the DF i.e. daylight factor. This is the most widely used index which defines the ratio of interior illuminance on a horizontal surface to the exterior illuminance on a horizontal surface under an overcast (CIE) sky. According to BREEAM standards [300], the minimum DF should be at least 2% for 80% of the space and according to CIBSE [296], [297] this should be at least 2% for 75% of the space.

Table 5.2. Recommended lighting levels in educational premises [297], [299].

| Type of area, task or activity | Lighting levels (lux) |
|---|---|
| Classrooms, tutorial rooms | 300 |
| Sport halls, gymnasiums, swimming pools | 300 |
| Auditorium, lecture halls | 500 |
| Practical rooms and laboratories | 500 |
| Technical drawing rooms | 750 |

Apart from daylighting requirements, the uniformity daylight ratio should also be met in order to achieve successful daylighting. Light uniformity describes how evenly light is spread over a task area. Moreover, high uniformity of light contributes to avoiding visual stress and thus to reduction of the risk for visual discomfort [301]. According to BREEAM, a uniformity ratio, i.e. minimum DF / average DF, of at least 0.4 or a minimum point daylight factor of at least 0.8% is required for sufficient daylighting in general classrooms. However, according to the Department for Education and Employment of the UK [302], uniformity ratio of at least 0.3 is accepted for side-lit spaces.

According to the study of Reinhardt, Mardaljevic and Rogers [303], dynamic daylight performance metrics are based on timed series of illuminances in buildings which take into consideration the entire year, the quantity and character of daily and seasonal variations of daylight for a given building, as well as irregular meteorological events. Such indicators are i) Daylight Autonomy (DA), defined as the percentage of the occupied hours of the year when a minimum illuminance threshold is met only by daylight, (ii) Useful Daylight Illuminances (UDI), which represents the percentage of time in which the daylight level is useful for the occupants and is divided into three intervals, i.e. too dark (<100 lux), useful daylight (100-2000 lux) and too bright with the possibility of glare issues and discomfort (>2000 lux), and (iii) Maximum Daylight Autonomy (DAmax) which is defined as a sliding level equal to ten times the design illuminance of a space. DAmax is often used as the percentage of a work plane in which the maximum accepted illuminance is exceeded for more than 5% of the occupied hours of the year. The minimum illuminance required for the buildings under study is 300 lux. Following the climate-based simulation and the daylight autonomy (DA), a space that receives sufficient daylight (>300 lux), at least half of the occupied hours of the year, is considered a well day-lit space [304].

Finally, excessive daylight is potentially undesirable and may cause glare issues. Glare is a measure of the physical discomfort of an occupant caused by excessive light or contrast in a specific field. It is dependent on the luminance distribution in the observer’s field of view [305]. Glare is typically categorized as either disability glare or discomfort glare [306]. Disability glare is defined as a sensation of annoyance caused by high or non-uniform distributions of brightness in the field of view and it may be caused either directly from the luminous source or through reflections [305]. Discomfort glare is defined as the irritating or even painful sensation that can be evoked from a bright visible light source in the field of view. Most glare-related indices or metrics aim at evaluating discomfort glare and are computed with equations that correlate luminance values to human glare sensation [298]. According to Andersen et al. [307], a credible prediction of glare using indices still poses significant challenges in the building as: (i) it depends on the observer's position, (ii) tolerance to glare varies depending on the individual, their background, their capability to adapt to the light environment, and (iii) the range of assessed luminance can be very wide. According to Carlucci et al. [301], the most appropriate metric to analyse absolute glare issues is the Discomfort Glare Probability (DGP) as it shows a stronger correlation with the user's response in terms of glare perception [308]. DGP is a short-term, local, one-tailed index assessing discomfort glare which is defined as shown in Equation (5.1):

$$DGP = 5.87 \cdot 10^{-5}\, \mathrm{E}_V + 0.0918 \cdot \log 10 \left[1 + \sum_{i=1}^{n} \left(\frac{L_{s,i}^{2} \cdot \omega_{s,i}}{E_V^{1.87} \cdot P_I^{2}}\right)\right] + 0.16 \qquad \text{(Eq.5.1)}$$

where $E_v$ is the vertical eye illuminance, produced by the light source [lux]; $L_S$ the luminance of the source [cd/m$^2$]; $\omega_s$ the solid angle of the source seen by an observer; $P$ is the position index, which expresses the change in experienced discomfort glare relative to the angular displacement of the source (azimuth and elevation) from the observer's line of sight. The equation is valid within the range of DGP between 0.2 and 0.8 and for vertical eye illuminance ($E_v$) above 380 lux. Specifically, the degrees of glare sensation are as follows: imperceptible (< 0.30), perceptible (0.30-0.35), disturbing (0.35-0.40), and intolerable (> 0.45).

## 5.4. Previous studies about lighting performance in educational buildings

Many research studies highlight that ensuring lighting quality in an educational environment is a rather complex task.  A series of different visual activities are performed within the classroom, such as reading and writing on desks and on the classroom writing boards, communication between children and the teacher etc. These activities require specific visual conditions in order to be successfully performed. However, only few studies have focused on the evaluation and improvement of daylighting in educational buildings, using various methodologies. Assessment of daylighting in classrooms of one school in Italy, using as a methodological tool the Daylight Factor (DF) as well as the dynamic climatic-based metrics of Daylight Autonomy and Annual Sunlight Exposure, was employed by Pellegrino et.al. [309] indicating insufficient daylighting performance of classrooms. Another study performed by Secchi et al. [310] highlights problems of overheating and glare in schools in Italy.  The study deals with retrofitting strategies for the improvement of indoor visual comfort (i.e. external horizontal or vertical louver shading devices) indicating their contribution to the improvement of daylighting uniformity and to the reduction of artificial lighting demands as a result of the non-use of internal curtains. For the evaluation of the different strategies, the DF and daylighting uniformity indicators were used. The findings of the research study performed by Axarli and Meresi [311], [312] in 9 classrooms of 5 schools in Greece are in line with the abovementioned research. Using objective observations, subjective reporting by the occupants and the DF indicator, the study evaluates the quality of lighting in the classroom. Despite high daylighting levels in all cases under study, the research indicates insufficient lighting distribution and glare issues during the summer period as a result of the use of unsuitable shading devices. A similar study for classrooms in Greece has also been undertaken by Theodosiou and Ordoumpozanis [313]. The study reveals that artificial lighting is used during working hours as a result of closed curtains which are used to control glare issues.

### 5.5. Chapter summary

This chapter has presented a review of the key literature on the theory of natural lighting. The chapter has established the significance of daylighting and reviewed the criteria given in the current standards for the evaluation of natural lighting. This chapter reviewed previous studies on daylight in educational buildings underling the positive impact of daylighting on the performance and health of their users. The literature review in the context of classrooms reinforces the knowledge gap regarding daylighting in educational buildings with students as the long-term occupants. The information provided in this chapter forms the theoretical framework of this research as a whole, and suggests the basis for developing a new approach to investigating the daylighting performance of secondary school classrooms in Cyprus.

Throughout the years, daylighting was considered an important factor in the design of schools rather than in the design of any other building. The positive impact of daylighting in the performance of students, the creation of a pleasant environment, the promotion of healthier conditions as well as the provision of energy saving has been well established over the years.

Current daylighting standards, e.g., CIBSE Guide A [297], IESNA [298] and European Standard EN 12464-1[299], define acceptable minimum lighting levels, uniformity and indexes for visual comfort for the design of buildings. In general, previous studies in schools of Mediterranean region show insufficient lighting distribution and glare issues during the summer period.

Although visual comfort in educational buildings is a multifaceted research field of high interest, the existing literature is rather limited in Cyprus. For the evaluation of the daylight performance and visual comfort in the typical classroom of educational buildings in Cyprus, an extensive investigation is still needed. Aiming at a holistic investigation of the research topic, the study is going to use both qualitative and quantitative research tools. The multi-criteria evaluation methodology introduces a holistic approach to the study of natural lighting performance and visual comfort, and thus contributes to the knowledge in the relevant field.

# Chapter 6. Climate change: observation, projection and review to literature

## 6.1. Introduction

The purpose of this chapter is to review the literature regarding climate change effects in Europe. This chapter reviews the climate change observations and projections based on the literature and investigate their effect on buildings. To achieve the general purpose of the chapter, firstly the climate change observation in Europe is provided associated with the projection of future climate change scenarios. Secondly, the study explores the impact of climate change on building energy use, thermal comfort and overheating. Moreover, a brief review of the previous studies related to the climate change adaptation and mitigation measures is performed. Finally, a chapter summary is provided.

## 6.2. Climate change observation in Europe

According to the current scientific consensus, warming of the global climate system seems to be unambiguous, as it is now evident from observations of increases in global average air and ocean temperatures, melting of snow and ice and rising global average sea levels [314].

Each of the last three decades has been successively warmer at the Earth's surface than any preceding decade since 1850. The period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere, where such assessment is possible (medium confidence). The globally averaged combined land and ocean surface temperature data as calculated by a linear trend, show a warming of 0.85 [0.65 to 1.06] °C over the period 1880 to 2012, for which multiple independently produced datasets exist (Figure 6.1).

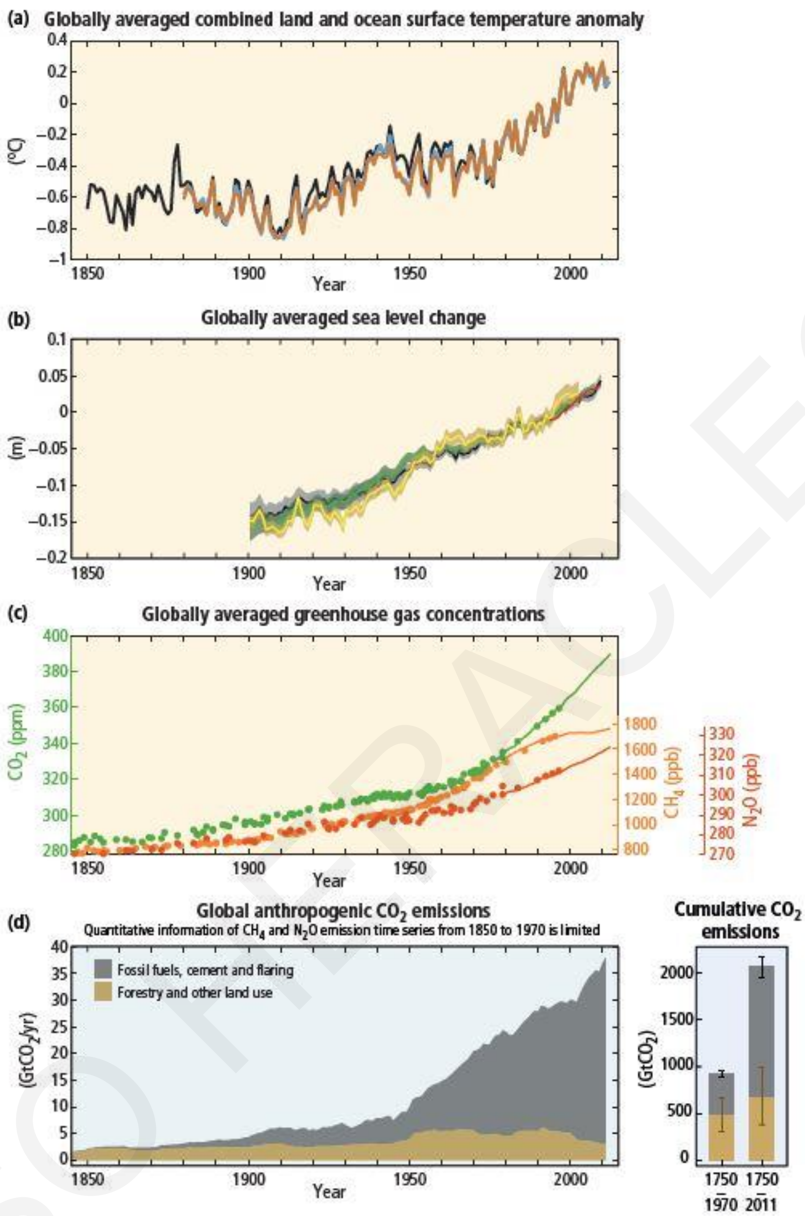



Figure 6.1. The complex relationship between the observations (panels a, b, c, yellow background) and the emissions (panel d, light blue background) [314].

The average temperature in Europe has continued to increase, with regionally and seasonally different rates of warming, being greatest in high latitudes in Northern Europe. Since the 1980s, warming has been strongest over Scandinavia, especially in winter, whereas the Iberian Peninsula warmed mostly in summer [315]. The decadal average temperature over land area for 2002–2011 is 1.3° ± 0.11°C above the 1850–1899 average, according to the Hadley Centre/Climatic Research Unit gridded surface temperature data set 3 [316], the Merged Land-Ocean Surface Temperature [317], and the Goddard Institute of Space Studies (GISS) Temp [318].

Since 1950, high-temperature extremes (hot days, tropical nights, and heat waves) have become more frequent, while low-temperature extremes (cold spells, frost days) have become less frequent. Since

1950, annual precipitation has increased in Northern Europe (up to +70 mm per decade), and decreased in parts of Southern Europe [315]. Winter snow cover extent has a high inter-annual variability and a non-significant negative trend over the period 1967–2007 [319]. Mean wind speeds have declined over Europe over recent decades [320] with low confidence because of problematic anemometer data and climate variability. Bett et al. [321] did not find any trend in wind speed using the Twentieth Century Reanalysis, (i.e. a project that has generated a four-dimensional global atmospheric dataset of weather spanning 1836 to 2015 to place current atmospheric circulation patterns into a historical perspective).

Europe is marked by increasing mean sea level with regional variations, except in the northern Baltic Sea, where the relative sea level decreased due to vertical crustal motion. Extreme sea levels have increased due to mean sea level rise [315].

On the European continent, Mediterranean Europe is expected to experience the most adverse climate change effects [322]. The Mediterranean region is already experiencing less precipitation in summer and rising temperatures, which have led to intense summer droughts. The Mediterranean region is expected to suffer from more extreme droughts in the coming decades, together with other regions, such as Central Europe [323]. According to a study performed in the EU Science Hub in 2018, average temperatures in the Mediterranean region have already risen by 1.4°C since the pre-industrial era, 0.4°C more than the global average (Figure 6.2).

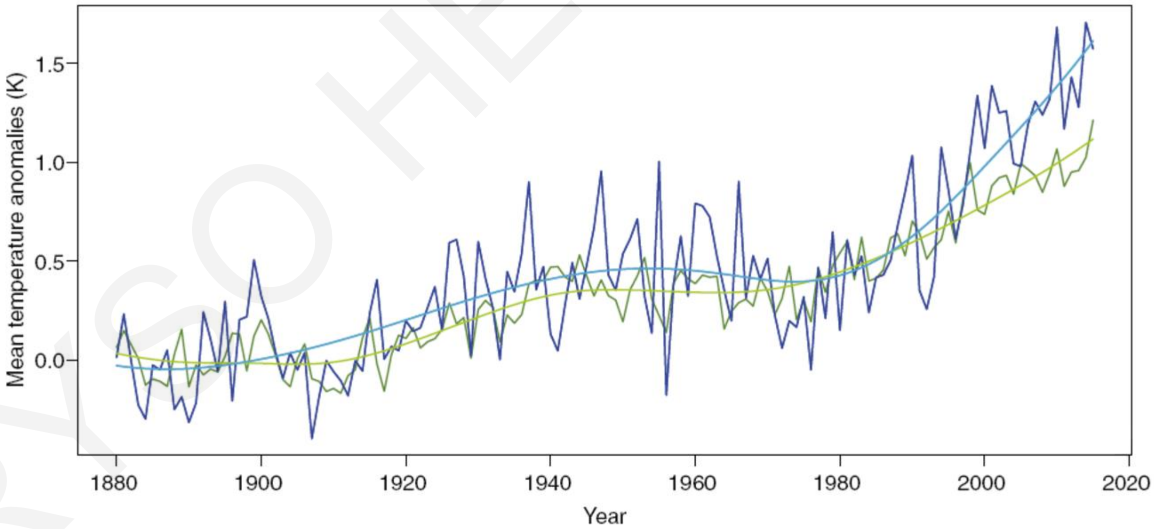



Figure 6.2. Historic warming of the atmosphere globally (green) and in the Mediterranean Basin (blue) [324].

Observed precipitation trends in the Mediterranean are characterized by high variability in space and in time, but climate models clearly indicate a trend towards reduced rainfall in coming decades [325]. The combination of reduced rainfall and warming generates strong trends towards drier conditions. Frequency and intensity of droughts have already increased significantly in the Mediterranean since 1950 [326]. During 2008-2011, for example the Middle East underwent a strong drought due to a large deficit of precipitation amplified by high evapotranspiration related to a strong warming (the

1931-2008 period has warmed by 1°C) and by an increase of water demand related to a strong increase of the population.

Similar to worldwide trends caused by warming and loss of glacial ice, sea levels in the Mediterranean have risen between 1945 and 2000 at a rate of 0.7 mm per year [327] and between 1970 and 2006 at the level of 1.1 mm per year[326]. There has been a sharp increase during the last two decades as sea level rise reached about 3 mm per year leading to about 6 cm rise and sea water acidity has significantly increased [324].

### 6.3. Future climate change scenarios

A report from the IPCC on the last decade published in 2014, which has gained the attention of scientists and academia worldwide, demonstrated that climate change has occurred mostly as a result of anthropogenic actions [6]. Depending on different scenarios projected by the IPCC, the level of greenhouse gas emissions will vary in the future. The measured data of global temperature during the period 1880-2012 showed an increase of 0.85°C, with an increase in warm days and nights and a reduction in cold days and nights. Moreover, the frequency of heavy precipitation has risen in North America and Europe.

Forecasts vary substantially which is indicative of how sensitive climate variables are in emission scenarios, for instance, temperature (Figure 6.2). The IPCC published the fifth synthesis report (A R5) for climate change in 2014 [6], in which projected climate change based on RCPs is similar to the fourth report (AR4) [328].

In the fourth report, scenarios are directed towards different options on how the future evolves and involve a number of essential "future" features including demographic change, economic development, and technological change.

The scenarios of group A1 feature an integrated world with fast growth in the economy, a rising population of nine billion in 2050, the rapid spread of novel technologies, and substantive social and cultural exchanges globally. Subsets to the A1 group vary depending on their technological focus; A1FI focuses on fossil-fuels (Fossil Intensive), A1B keeps an equilibrium between all energy sources and A1T targets non-fossil energy sources.

The worst-case scenarios are reflected in the A2 group of scenarios. These are enacted in a more fragmented world; a world where nations operate in a more independent manner, they rely on their own strength, the world population is increasingly rising, development and growth of the economy are more regionally-oriented, and technological change is not as rapid or unified.

On the other hand, the B1 group scenarios concern a more integrated world, that is more ecologically sensitive and these reflect the best possible scenarios. The B1 group scenarios feature fast economic growth as in A1, but shifting to more service and information-oriented economy; the population reaches nine billion in 2050, material intensity decreases and clean and resource efficient technologies are introduced while global solutions to economic, social and environmental strength are emphasized [328].

The fifth report (AR5) produced the Representative Concentration Pathways (RCPs) which are not as wide as scenarios employed in AR4. The RCPs involve a strict improvement scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and a scenario involving very high GHG emissions (RCP8.5). Other scenarios which employ no real measure to mitigate the results of emissions (baseline scenarios) result in options between RCP6.0 and RCP8.5 (Figure 6.1). RCP2.6 reflects the effort to maintain global warming below 2°C above pre-industrial temperatures implementing mitigation strategies.

Results produced by a number of climate model simulations indicate that the global mean surface temperature projected at world level will probably become warmer by 0.3°C to 1.7°C in RCP2.6, 1.1°C to 2.6°C in RCP4.5, 1.4°C to 3.1°C in RCP6.0, 2.6°C to 4.8°C in RCP8.5 for the years 2081-2100 relative to 1986-2005. The level of the rise in global warming relates to the measures and policies opted for at present and in the near future. Such measures impact in a direct manner on how fast we should expect gases to be trapped into the atmosphere [328]. Additionally, as shown in Figure 6.3, the effect of emission scenarios on global temperature does not show significant variation until 2050 (the difference in the prediction for 2040 for instance, with A1B is less than 0.3 °C compared to other scenarios); therefore, different scenarios do not affect the results related to these years (Figure 6.3).

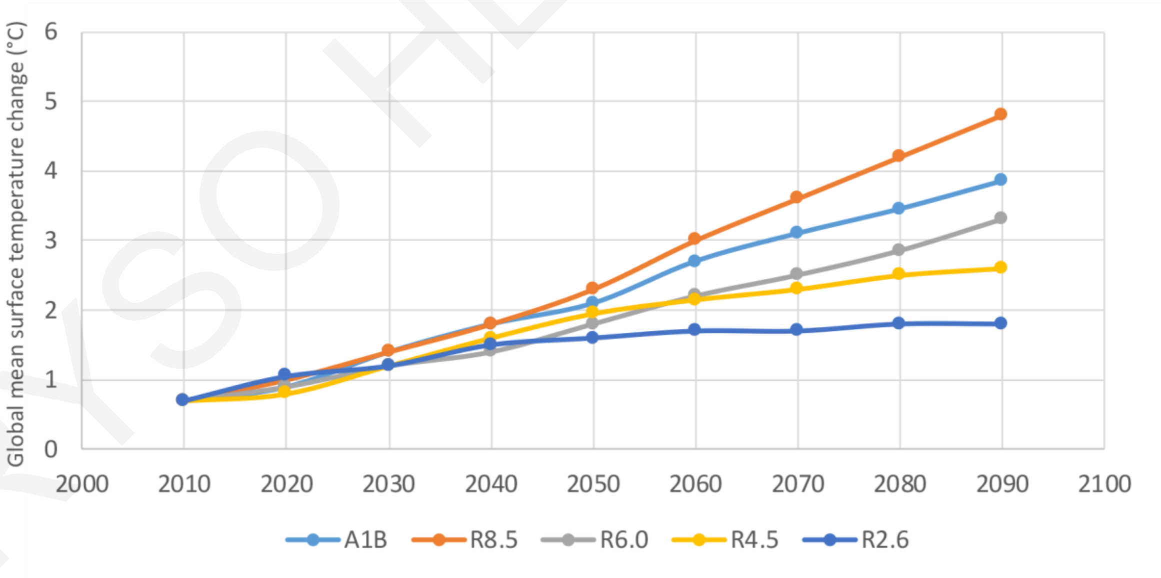



Figure 6.3. Projection that compares the changes produced in global mean surface temperature in different emission scenarios (RCP) according to the A1B emission scenario.

The last report from the International Panel on Climate Change in 2014 [314] highlights the Mediterranean as one of the most vulnerable regions in the world to the impacts of global warming. The models issued by IPCC cast different scenarios for the Region, but all of them agreed on a clear trend in the pattern of some climatic parameters. In terms of the thermal regime, the base scenario from 1980-2000 was used to estimate an increase in average surface temperatures in the range of 2.2 and 5.1 °C for the period 2080-2100. For the same period, the models indicate pronounced rainfall regime changes in the Mediterranean, and estimate that precipitation over lands might vary between -4% and -27% [329]. For each degree of global warming, mean rainfall will likely decrease by about 4% in much of the region, particularly in the south [6]. Dry spells will likely lengthen by 7% for 1.5°C global average warming [330] (Figure 6.3). Heavy rainfall events are likely to intensify by 10-20% in all seasons except for summer.

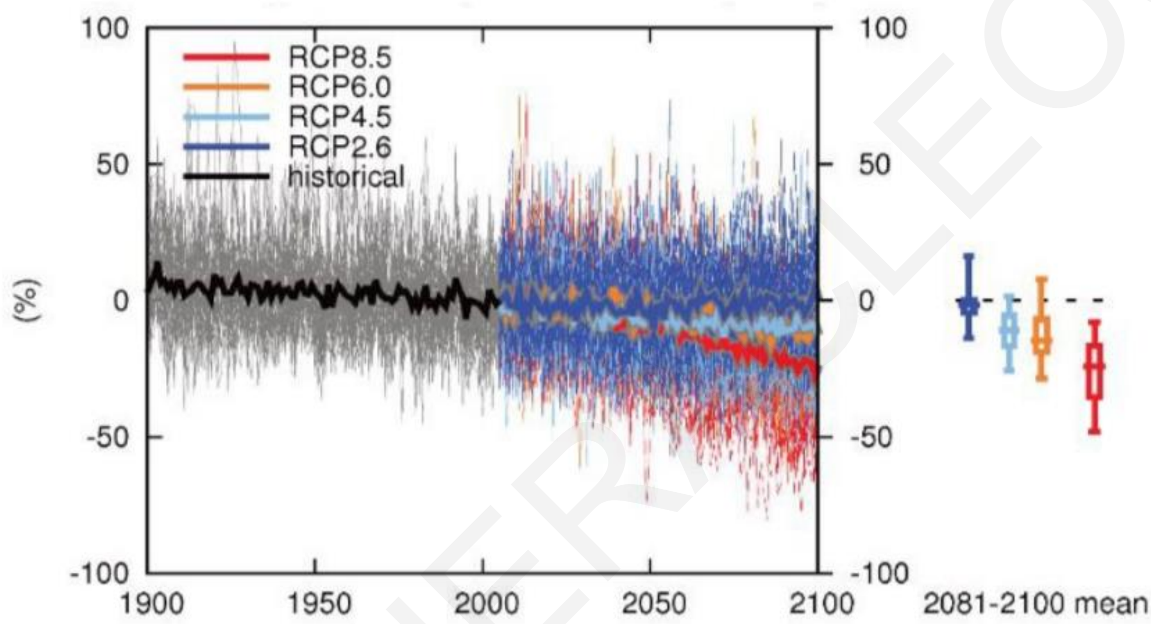



Figure 6.4. Change in precipitation relative to 1986-2005 in the region of southern Europe/Mediterranean (30°N to 45°N, 10°W to 40°E) in April to September under different scenarios [6].

According to a study conducted by the Cyprus Institute [314], average temperatures in Cyprus specifically, will increase by 1 to 3°C within 30 years, by 3 to 5°C in 50 years' time and 3.5 to 7°C in the late 21st century, which means that the Eastern Mediterranean and the Middle East will have the highest projected climatic changes compared to the rest of the world. Precipitation is expected to be reduced to an average rainfall of 10-50% per year in northern regions of the Middle East, Turkey, Greece and southern Italy. Spring and summer will experience most of the rainfall reductions.

At a closer look, the projected results for Cyprus in 2020 to 2050 suggest that temperatures will rise during hot summer periods reaching temperatures beyond 38°C for two extra weeks per year compared to the current situation. Additionally, an extra month of warm nights with minimum temperatures exceeding 25°C is expected, compared to the current situation [16]. According to the last report of the IPCC [6], the most modest scenario (RCP 2.6) projects an increase in average surface temperature of about 1.5°C, while the worst scenario (RCP 8.5) projects an increase of around 3-4°C by the end of the century, in Cyprus.

## 6.4. The impact of climate change on building energy use

The rise in temperature and future extreme events will naturally influence human life and activity significantly, as well as buildings and their occupational patterns. Based on the review study undertaken by Li et al. [4] concerning the impact of future climate on the built environment, Central and Northern Europe will experience a substantial reduction in heating needs and an increase in cooling needs. Specifically, the increase in cooling needs in residential buildings in the UK could double in $CO_2$ emissions by 2030 [6]; while, in Sweden the heating needs for domestic buildings may be reduced by 30% in Stockholm [4] and by 20-45% in Vaxjo [331]. Another study conducted by Moazami et al. [332] on the effect of climate change on apartments in Geneva, Switzerland concluded that the peak cooling demand would rise by 3.8% to 13.1%, while the heating demand will decrease more evidently in higher insulated buildings and colder locations. Contrary to this, the need for cooling in Southern Europe, will by far exceed the decreasing need for heating, thereby leading to higher total energy consumption [7]–[10]. Assimakopoulos et al. [333] note that the heating demand in Greece will be reduced by 90% while cooling could increase by a staggering 248% by 2100 (scenario A2). Santamouris and Kolokotsa [334] evaluated the impact of climate change, increased population and income growth on cooling consumption in residential buildings projecting an increase of up to 35% by 2050. Kapsomenakis [335] assessed the results of increased temperatures over the last 40 years on the energy consumption of office buildings and derived that cooling loads increase by about 5 $kWh/m^2$ per decade. The study of Suarez et al. [336] suggests that residential buildings in southern Europe will have double the cooling demand by 2050. In a humid subtropical climate, buildings will experience more adverse effects with a decrease of heating demand by 81% and an increase of cooling demand by almost 150% [337]. However, it should be noted that the percentage of increase of cooling demand and the percentage of decrease of heating demand is relevant to the reference heating/cooling ratio and determines whether the overall energy demand will increase or decrease as a result of climate change. It is crucial to note that the effects of climate change will be more adverse in urban areas due to the heat island effect, raising human discomfort [334]. The features of a building, its climate zone, as well as the topography and typography of the surrounding area, influence the degree of impact that buildings will receive from climate change.

## 6.5. Impact of climate change on thermal comfort and overheating risk

Under previous weather conditions, the number of overheating days and the amount of cooling demand was relatively low. The consequences of climate change exacerbate thermal comfort conditions as the existing facilities were not designed to meet the challenges caused by climate change [6], [338]. Climate change will lead to an increase in temperature that will significantly affect the indoor thermal environment and change the pattern of cooling demands [339].

The level of comfort (or discomfort) can be expressed by different quantitative measures such as the number of hours or percentile when the indoor temperature exceeds the so-called acceptable upper temperature limit or the PPD values. With higher outdoor temperature the risk of overheating is increased, particularly in case of internal loads and an absence of night ventilation.

Numerous studies have been conducted worldwide analysing the thermal comfort in educational buildings, employing different methodological approaches. Specifically, the evaluation of thermal comfort of schools has been conducted in temperate climate [160], [340], [341], in subtropical climate [168], [181]–[184], [342], [343], in tropical areas [344], [345] and the Mediterranean climate [159], [161], [163], [175], [176], [187]–[189], [346], [347]. Higher outdoor air temperatures in the future will lead to higher indoor temperatures, beyond acceptable comfort levels, thereby increasing the average duration of hours causing discomfort during the summer [334]. Escandon et al. 2019 [348], have undertaken a study which investigated the impact of climate change on thermal comfort in social housing stock in southern Spain, which states that discomfort hours will be increased by 35% in 2050. Moreover, they concluded that understanding future thermal behaviour could be used as a means of energy retrofitting during the decision-making process.

Several studies have assessed overheating risk in buildings and the significant changes in the building space conditioning energy use under anticipated climate conditions. The overall effect of the projected climate scenarios varies for different locations and building typologies. In several studies [28] potential temperature increase is used as proxy to investigate the effects of climate change on building energy use. Frank et al. [349] evaluated the implications of climate change for different building configurations in Zurich, considering mean annual air temperature increase ranging from 1 to 4.4 °C. The results show that the energy efficiency level of the building has significant impact on the thermal performance of buildings under climate change.

Dodoo and Gustavsson [350], explored the extent to which different climate change scenarios influence annual energy demand and peak load for space heating as well as cooling of multi-story residential buildings in the southern Swedish city of Vaxjo. The risk of overheating in buildings and the effectiveness of different overheating control strategies, including increased airing, solar shading and mechanical cooling with stand-alone room air conditioners, was evaluated using hour-by hour dynamic building energy balance modelling to analyse the implication of climate change. The research is quite extensive, analysing the building design versions based on the Swedish building code (BBR 2015) and passive house criteria [351]. The total annual operation of primary energy decreased by 37-54% for the building design versions when all strategies are implemented under the considered climate scenarios.

Panao et al. [352] assessed the Portuguese building thermal code and proposed newly revised requirements for cooling energy needs used to prevent the overheating of buildings in the summer. The study used steady-state methodology to calculate cooling energy needs. The results show that the required conditions are insufficient to prevent overheating and therefore the gain utilization factor, as an overheating risk index, is proposed according to an adaptive comfort protocol.

Building performance in correlation to overheating has been mainly studied in the residential sector, as well as in offices. Overheating in social housing in the UK according to the passive-house standards was explored by Sameni et al. [353] and their future performance by McLeod et al. [354]. Risks in future climates have also been investigated for multiple European locations employing the adaptive approach [355]. Jenkins [356] developed a probabilistic tool for assessing future climate overheating risk tested for buildings of domestic and educational use. Ascione et al. [357] studied solar shading strategies for reducing summer overheating in a contemporary well-insulated mutli-story office building in Berlin [358] by analysing cool coated shading systems used in housing. Gourlis and Kovacic [359] developed and analysed passive optimization measures and natural ventilation scenarios for the improvement of the indoor climate and reduction of summer overheating in manufacturing process loads in Austria causing thermal discomfort, thus enhancing workers' fatigue risk. For the assessment of overheating, the three criteria of TM52 adaptive approach were used. Finally, suggestions were made considering suitable retrofits based on the prevailing needs of the facility each time, hence supporting decision making for a more cost-effective initial investment.

While a growing number of studies have been reported on the implications of climate change for the energy and thermal performance of buildings, the existing literature is rather limited for the context of the southern Europe and especially for educational buildings. The impact of climate change on thermal performance of buildings may vary depending on geographic location and climate condition [360], [361]. For the evaluation of the overheating risk in the typical classroom of educational buildings in Cyprus, an extensive investigation is performed in the current thesis. The analysis is based on a dynamic hour-by-hour building energy balance modelling that focuses on the impact of climate change regarding projected temperature increases, on the thermal performance of the educational buildings and the effectiveness of different natural ventilation strategies for the mitigation of these events.

## 6.6. Previous studies for climate change adaptation and mitigation

Energy use and the associated emissions may double or even triple in the future due to several factors. This dangerous trend could be reversed if actions are taken in a timely manner. One can address climate change challenges in two ways; mitigation and adaptation. The first option entails finding ways to decrease and regulate energy use because of global warming, while the second endeavours to adapt to the current and future conditions within the built environment. While mitigation actions aimed at reducing the negative impacts of climate change are of high importance, there have been only a few studies which examined the impact of climate change and mitigation potential. On a policy level, many countries have established building energy codes for new buildings in order to comply with European Union Directives on low energy buildings. However, the improvement of the efficiency of the existing building stock remains a challenging task. Passive mitigation measures include the application of insulation, improvement of glazing efficiency, addition of shading systems or overhangs, natural night cooling ventilation, installation of green roofs and walls, as well as changing the solar reflectivity of the building. The performance of each passive strategy depends on the climatic conditions of each case of building under review.

Applying thermal insulation, could decrease heating and cooling needs by 23% and 20% respectively and the total by 16% based on a study undertaken in the UEA [362]; while, in a hot and humid climate (Brazil and Taiwan) one could reduce the total energy demand by 27% [363]. Based on a research carried out exclusively during the cooling season, an increase in insulation reduces discomfort hours by 48% [364]. In temperate climate, the reduction of heating demand rises up to 57% [365].

The installation of energy efficient windows ranges from 9% to 17% for heating demand and from 3 to 6% for cooling demand in various climates [366]. However, another study conducted in office buildings in Japan, which has a cooling-dominated climate, concludes that additional insulation and energy efficient windows increase the total energy use due to overheating [367].

Solar shading systems in most cases increase the heating demand, due to reduced solar gains, and decrease the cooling load. The reduction may vary depending on the climate. For example, the application of solar shading control in residential buildings in Brazil [363], Taiwan [368], Netherlands [365] and Sweden [351] reduces cooling demand from 30% to 90%, while in office buildings in Japan the reduction is less than 10% [369].

Natural ventilation is beneficial in the summer period when the external temperature is lower than indoor temperature. According to Shibuya and Croxford [369], night ventilation reduced the total energy of an office building by 10% in Sapporo, Japan. Nevertheless, Van Hooff et al. [365], have found that natural ventilation could decrease the cooling load for dwellings by up to 60%.

Several studies reported that mixed-mode ventilation is a very effective strategy for addressing climate change variations. This is confirmed by a study undertaken by Wang et al. [370] in medium office buildings in two different climatic conditions of the USA, as well as from the study by Dino and Akgul [371] in residential buildings in Turkey. The study finds that buildings which employ a mixed-mode for cooling purposes demand less energy than buildings which employ a single cooling mode, namely, air-conditioning. Moreover, using heat recovery ventilation decreases the heat loss from ventilation dramatically, and hence the hours of discomfort. Kragh, Rose, and Svendsen state that heat recovery ventilation can reduce the amount of heat lost by 80-90% and the overall heat loss by 30-60%, depending on the insulation level of the building [372].

## 6.7. Chapter summary

This chapter has presented a review of the key literature on the impacts of climate change. The chapter has observed climate change in Europe and reviewed the future climate change scenarios. This chapter reviewed the impact of climate change scenarios on building energy use, on thermal comfort and examined its contribution to overheating risk highlighting the importance of climate change adaptation and mitigation. The information provided in this chapter forms the theoretical framework of this research as a whole and suggests the basis for developing adaptation and mitigation measures to climate change in order to suggest specific improvements for thermal and energy performance of educational buildings.

Thermal discomfort leads to the need for heating in the wintertime and cooling in summertime in school buildings in Cyprus. The consequences of climate change will only further exacerbate these energy demands, as the existing facilities like many others in Europe, were not properly designed in order to meet the challenges caused by climate change [6], [338]. It has become clear that climate change will lead to an increase in hot days that will significantly affect the indoor thermal environment [339]. According to the IPCC, (Intergovernmental Panel on Climate Change), the extreme events that appear currently in southern Mediterranean countries may be more frequent in the next decades of the century [373]. Discomfort in schools may create unpleasant conditions such as cold and heat stress for the occupants, resulting in the increase of health risks and the reduction of productivity [359]. Predictive modelling assumes that productivity may be reduced globally by up to 20% in hot months by the year 2050 if no action is taken [374]. In naturally ventilated buildings, the achievement of thermal comfort is more important than in-use energy, as only little energy is used to regulate the indoor environment. However, global warming may also influence buildings' energy use, operational cost, and may cause deterioration of building structure [375]–[379]. At present, there are two opportunities to build sustainable, climate resilient infrastructure: the first is through the construction of new buildings and reconstruction following e.g. extreme weather events, while in all other instances, buildings must be retrofitted if they are to be future-proofed for predicted changes in climate. Upgrading existing buildings is a crucial issue in the context of sustainable architecture, as a holistic replacement of existing building stock will come at a great environmental cost.

Climate change surveys have been performed for only a limited number on educational premises. Understanding the impact of climate change in buildings enhances the development of appropriate measures to mitigate the effect of climate change in the current and future climatic conditions. The outcomes of previous studies reinforce the need for further research in the field, particularly in naturally ventilated secondary schools in east-Mediterranean region. This research conducts an extensive study to contribute to the understanding of the impact of climate change in the current and future climate change scenarios in educational buildings in Cyprus with the aim of improving the performance of classrooms.

# Chapter 7. Technical solutions for the achievement of required overall comfort conditions in buildings

## 7.1. Introduction

The purpose of this chapter is to develop a conceptual framework and build a theoretical basis for introducing strategies that can be used in buildings to achieve the required overall comfort conditions. Different techniques can be used to improve comfort and energy performance of buildings including (a) passive techniques i.e. construction and architectural elements, (b) technical systems, i.e. fans, HVAC systems and energy efficient lighting systems and (c) operation of the building by occupants. Passive techniques and proper operation of buildings reduce demand and improve comfort using less energy; however, technical systems depending on their application consume less or more energy. Specifically, the installation of air conditioners has several disadvantages related to technical requirements, environmental and energy policy, health and operating costs. They generate permanent operating energy costs, as well as system maintenance, repair and replacement costs, which are not negligible. Also, if not properly maintained they cause a deterioration of the quality of the indoor environment, which contributes to the growth of bacteria, mould and fungi resulting in serious health risks for users. The installation of air conditioners is contrary to European policies and the now established scientific approach, in relation to the energy efficiency of buildings and thermal comfort. Any use of a technical system should follow the energy upgrading of the building envelope and other taken measures to reduce energy demand. The Building Energy Efficiency Directives (2010/31 / EU, 844/2018 / EU), which are the main existing legislation on a European Union level to improve the energy efficiency of buildings, emphasize the promotion of nearly zero energy buildings (nZEB); therefore, this thesis gives emphasis on passive and mild technical systems. To achieve the general purpose of the chapter, firstly the study reviews the enhancement of the passive measures including thermal insulation of the building envelope elements and transparent surfaces, the installation of technical shading and sun protection systems, the planting and the rational management of direct natural ventilation through the proper operation of external openings. Secondly, the use of moderate active systems such as ceiling fans and ventilation systems with dynamic control of their operation is described. Finally, a chapter summary is provided.

## 7.2. Technical solutions for the improvement of thermal comfort

The main purposes of the technical solutions regarding thermal improvement are to increase the thermal revenues of the building from the incident solar radiation during the heating period and to avoid unwanted heat gains and overheating in order to decrease the possibility of use of technical systems.

### *7.2.1. Enhancement of the thermal insulation of the building envelope elements and transparent surfaces*

Building envelope that includes the exterior walls, roof, floor, windows and doors are in constant connection with the external weather conditions on one hand and internal loads on the other. Therefore, the purpose of the envelope is to protect against unwanted external exposure, such as wind, rain, excess sun, dust, noise, etc. while allowing beneficial connection between the interior and exterior spaces via windows for fresh air and ventilation, natural daylight and pleasant views. The enhancement of **thermal insulation** of the building envelope aims to reduce the heat losses to the external environment during the heating period and to minimize the heat gains during the cooling period [349], [380], [381], therefore improving **thermal comfort**.

The construction interventions to the building envelope refer to the thermal insulation of the external masonry, the thermal insulation of the roof and the replacement of single-glazing with energy efficient glazing.

External insulation on the walls can achieve higher levels of insulation with little risk of moisture problems either internally or within the wall structure, assuming it is correctly installed and also maintains the thermal mass of the building by keeping the masonry within the insulation envelope. Moreover, external insulation prevent thermal bridges and covers any gaps and cracks in the wall.

Internal insulation on the walls may be easier to accomplish and do not affect the outer appearance of the building; however, once the building has any damp problems, the effect of insulation would be ruined. Also, internal insulation reduces the size of the room, limit the ability to hang very heavy objects from the walls and favours the formation of thermal bridges at the meeting points of structural elements. Internal insulation allow the room to be cooled or heated quickly but once the system is switched off, it does not have the ability to keep it long.

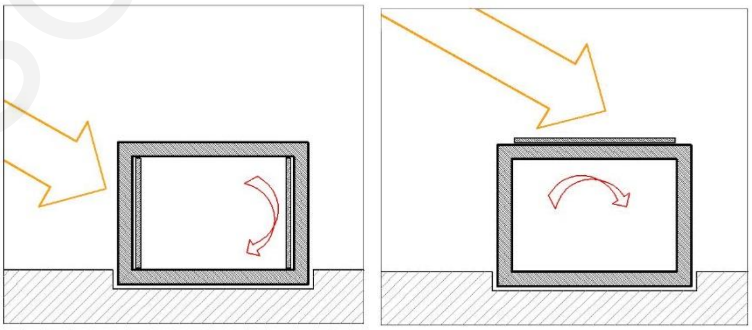


Figure 7.1. Design illustration of internal thermal insulation on the wall and external thermal insulation on the roof of the building [38].

### *7.2.2. Utilization of solar radiation*

Utilizing solar radiation (**direct solar gains**) to heat the building can contribute to a significant reduction in conventional energy consumption during the heating season. In order to choose the most suitable orientation, solar radiation is also considered during the cooling period, during which the solar gains are undesirable [349].

The utilization of solar radiation through the south windows is generally desirable and ideal during the heating period as south facing windows receive the sun's heat energy to warm the building and can easily keep the building cool with a shading system (or an overhang) during the cooling period.

Openings to the north help to improve the quality of lighting in the area because they only receive diffused and not direct light and are recommended for summer, but should be limited because they have large heat losses and minimal gains in winter.

East and west openings have the worst behaviour all year round, so they are only recommended where necessary for lighting or viewing purposes. Especially western openings are very unfavourable in summer, as they receive direct sun in the afternoon. In general, in the eastern and western openings, shading should be provided, preferably the external and vertical type [382].

### *7.2.3. Installation of technical shading and sun protection systems*

**Shading systems** are defined as the structural elements that are integrated into the envelope of the building for the purpose of sun protection and the possibility of controlling the light radiation of the interior spaces. Proper sun protection of glass surfaces is the most essential measure to ensure **thermal comfort** during the cooling period as well as **daylight control** throughout the year. Moreover, shading systems can enhance the thermal and sound insulation. According to the literature [383], [384], more suitable sun protection of the southern openings is achieved by the use of horizontal louvers or blinds, while the eastern and western openings by the use of vertical blinds, awnings or grids.

A combination of the above is a suitable sun protection for all orientations. Shading systems are classified into:

- Exterior shading systems, i.e. shading systems that are placed on the outside of the openings.
- Internal shading systems, i.e. shading systems that are placed on the inner side of the openings.
- Shading systems that are applied between glass panes.
- Shading systems, integrated in openings.

They are also classified into:

- permanent shading systems (e.g. horizontal overhangs, fixed blinds, lighting shelves) and
- movable shades:
    - Reclining: Reclining shading systems can be completely removed from the opening (e.g. outer opening leaves, awnings, Venetian blinds).

- Customizable: Adjustable shading systems that cover part of the opening and can be adjusted, for example, they can be rotating, sliding and so on (e.g. blinds, canopies).

More appropriate shading is ensured by the use of external movable shading, as it interrupts the sunlight before entering the interior and ensures shading control. The installation of rotating vertical blinds, provides controlled sun protection against fixed devices for different periods of the year and hours of the day. It is noted that the requirement to handle sun protection devices is the subject of practical knowledge and participatory action in the context of environmental education.

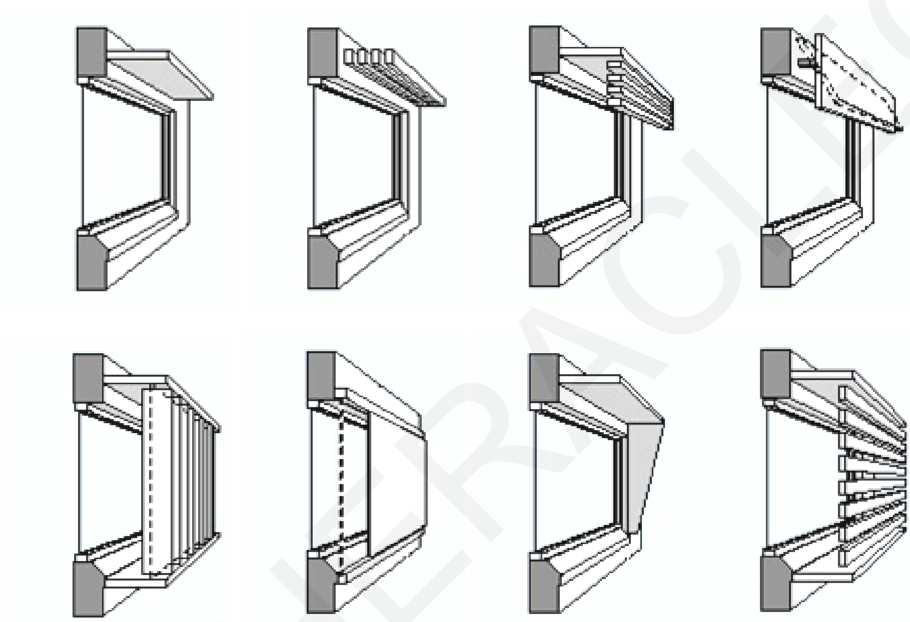


Figure 7.2. Alternative ways of sun protection for openings for south (top) and east, west and south orientation (bottom) [38].

### *7.2.4. Vegetation*

The possibilities of energy savings from interventions in the surrounding area of the building are mainly related to measures to improve the **microclimatic data**. Such is the use of suitable **vegetation** for sun protection of the façades during the cooling period and the exploitation of the solar gains during the heating period, through the use of the water element to achieve cooling by evaporation and the use of appropriate coating materials to reduce surface temperatures [38].

Vegetation can block, filter and divert air flow, thus affecting the natural ventilation of buildings. In particular, evergreen trees in the direction of prevailing winds can be used as barriers to airflow, deflecting some of the unwanted cold winds. During the summer, trees ensure a reduction in the temperature of the winds passing through the foliage (due to evaporation and perspiration), improving the indoor comfort conditions through natural ventilation [383]–[385].

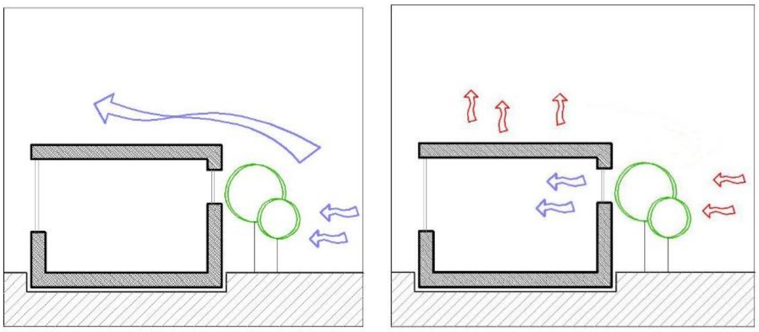


Figure 7.3. Design illustration of cold wind diversion during the winter season and improvement of microclimatic data during the summer, due to evergreen planting in the direction of the prevailing winds [38].

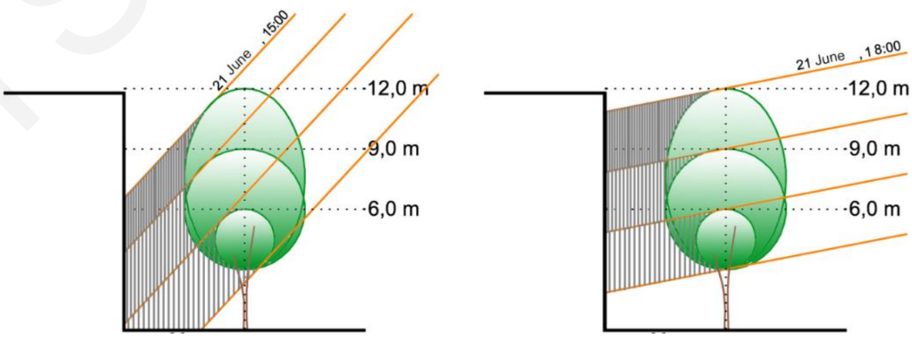
Vegetation in the outdoor area of the building, ensures significant reduction of solar radiation by achieving a reduction in surface soil temperature during the day.

Proper vegetation can significantly contribute to the sun protection of the façades during the cooling period and at the same time to the exploitation of the solar gains during the heating period.

On the south side of the building, the planting of deciduous trees contributes to the shading of the openings in the lower floors. However, the use of an artificial sun protection system is dictated by the large angles of solar altitude that characterize the south orientation during the summer months.

On the east and west sides of the building, planting deciduous trees can greatly contribute to shading, given the low angles that characterize the sun in the morning and afternoon, making planting a measure of sun protection in the east and west façades. The shading achieved depends to a large extent on the geometric characteristics of the trees (height, diameter and crown shape), the distance from the façades of the building and the distances between the trees.

The investigation shows more effective shading of the west and east sides of the school building specifically by deciduous trees, when the tree lines are at a short distance from the façades and the trees are no higher than the façade [38].



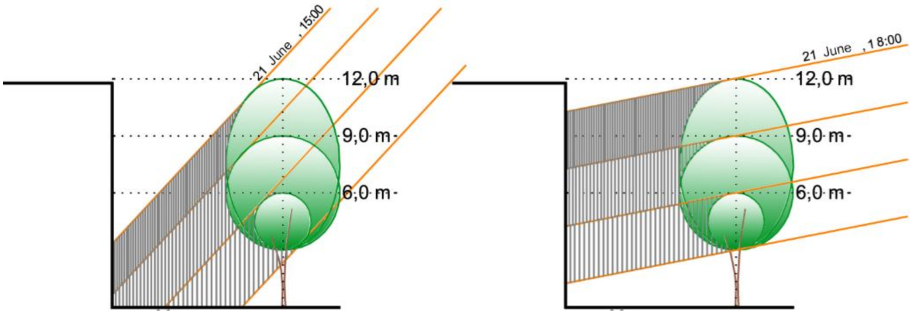



Figure 7.4. Investigation of shading design of the east and west sides of the building with different forms of trees at distances of 6 meters (above) and 9 meters (below) from the façade of the building [38].

**Surface coatings** with vegetation cover record the best thermal behaviour during the summer season. Plants have a relatively high rate of absorption; however, they do not overheat, as they use solar radiation for their plant functions. The surface temperatures of the various vegetation surfaces are even in the case of dry land cover, much lower than the corresponding temperatures of the dark, artificial building materials that form the majority of the unstructured surfaces of school buildings [385], [386].

For the choice of coating materials, it is important to ensure the water cycle, which is largely related to its penetration into the aquifer. The proposed outdoor materials and the construction details of their application, must be water permeable, ensuring the passage of rainwater to the ground.

Figure 7.5. Indicative photos of water-permeable materials and surfaces [387].

### *7.2.5. Window operation for natural ventilation*

The characteristics of the Mediterranean climate make **natural ventilation** a particularly effective strategy for improving thermal comfort conditions, both during the summer season and on the hottest days of the intermediate seasons. Natural ventilation aims to remove heat from the human body (direct physiological effect), cool the indoor spaces, cool the structural elements of the building envelope (indirect physiological effect) as well as to improve indoor air quality. Utilizing natural ventilation to cool buildings requires a sufficient temperature difference between indoor and outdoor temperatures [388]–[390].

The bioclimatic strategies of natural ventilation are classified into cross ventilation, night ventilation and stack effect ventilation. Cross-ventilation relies on wind force to produce pressure differences between the indoor and outdoor of the room, which in turn lead to internal air movement and heat removal from the interior. Ventilative cooling by buoyancy relies on temperature differences between the indoor and outdoor of the space to produce pressure gradients across the vents and drive the ventilation. Night ventilation ensures thermal discharge and cooling of the building envelope, thus reducing the cooling needs for the next day. This effect is enhanced by the thermally exposed mass of the building, so that it is possible to store the "cold" during the night [384], [391], [392]. The ventilation strategies accelerate airflow and ensure a pleasant feeling due to the air currents that are created.

There are different factors that affect the effectiveness of ventilation strategy, i.e.:

• Orientation of openings in relation to the blowing winds.

• Air inlet and outlet opening area ratio.

• Area and proportions of openings in relation to the geometry of the interior (depth, height).

• Height position and arrangement of openings in plan-view

• Type and details of openings (e.g. opening, sliding, retractable, rotating).

• Internal barriers (e.g. furniture, masonry).

• External barriers (e.g. adjacent buildings, planting, natural terrain).

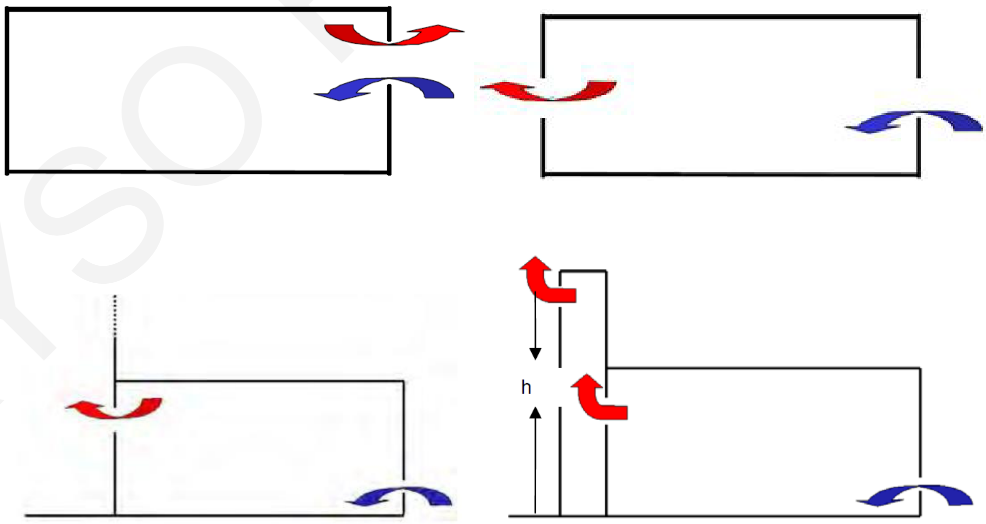



Figure 7.6. Ventilation strategies (a) single-sided, (b) cross-ventilation, (c and d) stack effect.

### *7.2.6. Evaporative cooling*

The positive effect of **water** on the improvement of microclimatic data is due to evaporative cooling. Direct evaporative cooling includes cooling systems, which channel indoor air, which previously passes through a water surface and is cooled due to water evaporation. They are, therefore, systems that utilize the water element for the direct passive cooling of the interiors [383], [391]Therefore evaporative cooling can passively cool building users through the reduction of internal temperature, the increase in relative humidity levels, the enhancement of natural ventilation, and the filtering of the levels of dust in the outside air. Evaporative cooling can be applied in the form of free water surface, water jet, or artificial fog systems [384].

Indirect evaporative cooling includes cooling systems, which use the evaporation of water to cool the structural elements of the building envelope (e.g. roof, masonry). Indirect evaporative cooling takes place without increasing the internal humidity, as in the case of direct evaporative cooling systems, i.e. roof pond or roof pool. A roof pond is a system that utilizes indirect evaporative cooling. A roof pool is the heat-insulated water tank on the roof of a building, which utilizes the evaporation of water to cool the interior.

### *7.2.7. Maximize the green area by creating green roofs or façades*

A **green or a living roof** is defined as the upper level or part of the upper level of a building, which is covered with vegetation. There are three main types of planted roofs depending on the type of vegetation: intensive, semi-intensive and extensive. In the intensive type, low and high vegetation can be developed, such as a variety of plants, shrubs, trees, etc. In the expansive type, only low vegetation can grow such as moss, lawns, flowers, shrubs, etc. In the semi-intensive type, medium-height plants such as lawns, ground cover plants, herbaceous plants and small-medium shrubs can be grown. Green roofs are also referred to as roof gardens. In addition to its bioclimatic function, the green roof is used as a place of gathering, rest and social activity, utilising a space otherwise unused more often than not [48], [384].

**A green façade or a living wall**, is a wall completely or partially covered with greenery. A green façade with climbing plants uses a trellis system to hold the vines of plants that are rooted in the ground or in containers. Green façades offer economic, environmental, aesthetic and physiological benefits to the urban environment [356].

The bioclimatic characteristics of both green roofs and façades are the following:

• Control of sunlight and shading.

• Reduction of solar thermal gains, absorbed by the roof/façade in relation to roofs/façades covered with hard materials.

• Reduction of the air temperature of the local environment through evaporation of the foliage of the vegetation.

• Reduction of the surface temperature of the materials.

• Wind protection - Reduction of cold air currents.

• Strengthening the thermal insulation protection of the building envelope.

• Improvement of indoor thermal conditions.

• Enhance sound protection.

• Reduction of the effect of the urban heat island phenomenon.

• Limitation of pollutant gases in the atmosphere.

• Effect on human comfort (sense of well-being and creating a pleasant mood of users with the environment).

Figure 7.7. Green roof at the British Horse Society headquarters [393].

Figure 7.8. Green façades systems [394].

### *7.2.8. Installation of ceiling fans*

The installation and use of **ceiling fans** in indoor spaces can improve thermal comfort conditions. The heat dissipation from the people in the spaces, due to the movement of air from the operation of the ceiling fan, ensures an increase of the thermal comfort limit by 3 °C for an air speed of 0.9 m/s [45]. In this way, the feeling of thermal comfort is ensured at a significantly higher temperature. In addition, during the winter it can work in the opposite direction and transfer the warm air that is in the high points of the space downwards.

## 7.3. Technical solutions for the improvement of air quality

The effects of indoor air quality on health, productivity and user mood demonstrate the need to ensure adequate air quality inside buildings. Great attention has been given by the scientific literature to microenvironments where high pollutant emitters are typically located, such as homes [395], [396], offices [397], [398], schools [398] and other working environments [399].

### *7.3.1. Natural ventilation through openings*

**Natural ventilation** is a much-preferred ventilation and cooling strategy by users and experts alike, due to both the high air quality they ensure and the simplicity and dynamics of their operation. Natural ventilation can reduce $CO_2$ levels and other contaminants to acceptable limits. [251]. Often, natural ventilation is associated with the manual opening and closing of windows to freshen and cool the indoor environment.

### *7.3.2. Ventilation through technical system*

The installation of technical ventilation systems in buildings provides **controlled ventilation** and ensures the required air exchange. It is recommended throughout the year, especially during the winter months, a period during which the level of air quality inside the buildings deteriorates, given that the openings are kept closed to reduce heat loss through ventilation, as well as during the summer season when increased ventilation needs are required to reduce the thermal loads of the building envelope [390].

### *7.3.3. Vegetation*

For the improvement of outdoor air quality, dense and appropriate **vegetation** could be introduced in the surrounding area of the building. The contribution of the natural element, in addition to the production of oxygen and the simultaneous capture of carbon dioxide, refers to the ability of plant foliage to act as a filter to retain a significant percentage of particles in the atmosphere and harmful components of the air [384].

### *7.3.4. Avoidance of pollution source*

In case of external pollution from a specific source, the windows should remain closed in the direction of the source of pollution in order to improve indoor conditions. The required ventilation can be provided through technical support on the opposite side of the classroom. This ensures a reduction in the concentration of pollutants inside the rooms and consequently the exposure of users to them.

## 7.4. Technical solutions for the improvement of visual comfort

The main purposes of the technical solutions regarding visual improvement are to utilize, penetrate and achieve uniform distribution of natural light inside the building to avoid glare caused by direct sunlight on the working plane or strong contrast of lighting, to reduce artificial lighting and to improve the technical support systems.

### *7.4.1. Transparent elements for natural lighting penetration*

**Transparent elements** of natural lighting penetration can be proposed for the building envelope to improve visual comfort conditions of users. They are the simplest natural lighting strategy in buildings and are distinguished in side openings and roof openings. Transparent elements improve the levels of natural light in the interior, improve the uniformity and enhance the visual communication with the external environment [383], [389].

### *7.4.2. Advanced / innovative natural lighting systems*

To enhance natural light and improve visual comfort conditions there are also some advanced / innovative natural lighting systems which redirect / deflect or transmit light radiation to the depths of the internal space. These systems are applied or integrated in openings either internally or externally or between the panes. They are classified into three main categories:

• Reflectors and lighting shelves.

• Built-in elements in openings.

• Lighting transmission systems.

**Reflectors** are reflective horizontal or sloping devices (blinds), which redirect light radiation to the inner ceiling. They are applied externally or internally to the side-openings and can be either fixed or rotating.

The **lighting shelves** are horizontal, slightly inclined or curved, fixed or moving reflective devices, that are placed on the upper part of the side opening, dividing it into two parts (lower part and upper part / clerestories). Lighting shelves extend inside and / or outside the panes. Their upper surface is mirrored or made of diffuse materials [400].

Figure 7.9. Reflectors and lighting shelves [400].

Built-in elements in openings include **prismatic acrylic glasses** which are refractory devices of incident sunlight, made of transparent materials (usually transparent polymers),consisting of a flat and a prismatic (toothed) surface and acrylic sheets with laser-cut incisions which are acrylic sheets, which have parallel notches with laser-cut, creating transparent parallels of deflection of the incident radiation. Laser-cut section acrylic sheets are placed in the gap of two panes of the building element. Both systems aim to improve the uniform distribution of natural lighting and secure greater penetration of natural lighting and control glare near the side openings [401].

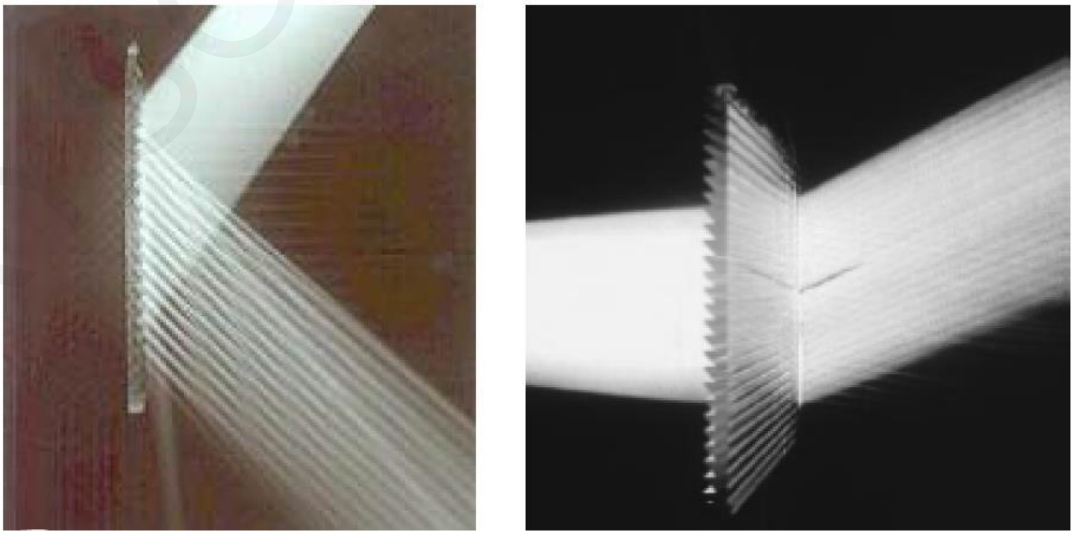


Figure 7.10. Prismatic acrylic glasses [401].

In the lighting transmission systems, **lighting ducts or light conductors** of light tubes are included. They consist of three distinct parts: an external transparent light collector, which is integrated into the roof (e.g. transparent acrylic canopy), a tube system (vertical or inclined), which is applied to the external collector and a transparent device at the bottom of the tube which emits diffused light inside (diffuser). The inside of the tube is made of highly reflective materials (e.g. mirrors, metal coating). These systems are appropriate for large-scale building complexes (with deep floor plans) and in central areas of the building with limited access to natural light or without access to natural light.

Figure 7.11. Light tubes [402].

7.5. Technical solutions for the improvement of the conditions of functional and aesthetic comfort

There are also **other factors** that contribute to the overall experience of space in schools that are related mostly to the improvement of functional and aesthetic comfort. These factors refers to the number of students per square meter, to the functional reorganization of the classrooms and in the aesthetic upgrade of the classrooms. The functional integration of the classrooms offers the possibility of unified activities. The above favors the development of alternative ways of teaching and ensures conditions of functional multiplicity and flexibility in the material infrastructure of the educational environment, while ensuring a high level of operational comfort of users [38].

Regarding the aesthetic upgrade of the teaching space, strengthening the classrooms with educational elements, cultural or other visual stimuli that will ensure a multifaceted perceptual result can affect the comfort of the users. Utilizing the possibility of posting educational or cultural material, contributes in this direction. The use of color and modern materials ensures the removal of the standard and indifferent expression of the standard classrooms.

In addition, the aesthetic upgrade of the classroom can be achieved by upgrading the functional equipment (desks, seats, hanging tables) and less important elements such as curtains, wastebasket, etc. The above, in addition to aesthetic improvement, ensure connection of visual stimuli (images) with the content of the training process [38].

### 7.5. Chapter Summary

The proposals for improving the environmental comfort conditions mentioned in the previous paragraphs can significantly contribute to improving the overall comfort conditions of existing school buildings. They refer to the improvement of the thermal comfort, visual comfort, and air quality conditions of the typical classroom as well as functional and aesthetics comfort. The measures and possibilities of intervention extend beyond the building envelope to the surrounding area of the typical school building.

In addition to improving the comfort conditions and quality of life of users, the proposed measures and strategic actions refer to improving the energy behaviour of the school building, ensuring a significant reduction of energy requirements, with favorable environmental consequences.

# Chapter 8. Economic assessment approaches

## 8.1. Introduction

One of the major challenges facing the achievement of nearly zero energy needs in existing buildings is the economic issue [403]–[405]. Barriers such as high investments, long payback periods and perceived credit risk hamper energy retrofitting strategies. The evidence of economic gains of energy retrofitting investments in existing buildings still seems rather limited [405], [406]. Consequently, many costumers see high operating cost and poor indoor environment as an acceptable alternative to the time-consuming, disruptive and risky renovation processes. Life cycle costing could then be an important decision factor to investigate the benefits and risks of investments in the building renovation sector. The purpose of this chapter is to develop a conceptual framework regarding economic assessment approaches and how these can become applicable to the building sector. To that end, this chapter reviews the theoretical introductions and foundations of life cycle cost analysis, and the important parameters for the calculation of life cycle costs and then argues for the necessity of sensitive analysis. Moreover, a brief review of previous studies that follow economic assessments of building retrofitting actions is provided. Finally, a chapter summary is provided.

## 8.2. Defining the life cycle costing

### *8.2.1. The concept of Life Cycle Costing*

Life Cycle Costing (LCC) has become increasingly important in construction over the last few years. Life Cycle Costing is an economic evaluation technique that concerns the assessment of the total cost of an asset over its operating life, including initial capital costs, maintenance costs, operating costs and the cost or benefit of the eventual disposal of the asset at the end of its life [407]. Life Cycle Costing is a decision-making tool, a management tool, and a maintenance guide. It is a decision-making tool in the sense that it could be used to select amongst alternative projects, designs, or building components. It is a management tool in the sense that it could be used to estimate the costs that will incur during a building's life. It is a maintenance guide in the sense that it could be used to forecast the maintenance and operating tasks that will incur at each year of a building's life [408].

### *8.2.2. Life Cycle Costing Techniques*

Life Cycle Costing could be applied at any stage of procurement. It could be applied at the inception stage to select among alternative projects. It could be applied at the detailed design stage to select among different design options or building components. At the inception stage where only the client requirements are known, the life cycle costs are estimated in broad terms based on costs that incurred in similar buildings in the past. As the design of the building becomes more detailed, the life cycle costs are estimated in more detail too. At the late design stages where the individual building components are known, the life cycle costs are estimated based on performance and cost data of the building components. For example, by knowing the price and life expectancy of a building component as well as the cost and frequency of all the maintenance and operating activities associated with that component we can estimate its life cycle costs. The life cycle costs of all the components together with the building-wide costs, such as energy consumption and insurance costs, constitute the life cycle costs for the building [408].

The estimated costs at each year of the building's life must be discounted to make proper allowance for time value of money and enable the comparison of the alternatives on a common basis [58]. What is meant by time value of money is that money has time value, as money set aside today would increase every year by the net inflation interest rate. This means that the present value of a future sum is less the further away in time the sum is due to be received or expended. To put it in another way, we have to set aside less today in order to meet a higher expenditure in the future. Calculating the life cycle cost of an option by merely adding up the constituent costs would be incorrect as to do so would be to ignore the timing of those costs. Rather, the costs should first be converted to present values and then added up to compare the different options on a common basis. The most common comparison measure used is the Net Present Value (NPV). However, other measures, such as the Equivalent Annual Cost, Payback Period, Return on Investment, and Saving to Investment Ratio could also be used [409]. The risk associated with each option might also be taken into account. Various risk assessment techniques could be used to assess that risk. For example, sensitivity analysis could be used to assess the impact of a change in an input variable on the life cycle costs of an option. Or, Monte-Carlo simulation could be used to obtain a range of possible values for the life cycle costs of the option [410].

## 8.3. Calculation of the Life Cycle Costing

There are several different standards available to guide a LCC analysis (ISO 15686-5:2017, EN 15459-1:2017, NS3454, ASTM). All have different cost categories and slightly different cost breakdown structures. The importance of using Life Cycle Costing in the building sector has been attested at regulatory level in Europe by Directive 2010/31/EU, which established that Member States shall calculate "cost optimal levels" of minimum energy performance requirements using a comparative methodology framework according to the consequent Commission Delegated Regulation and its Guidelines [411] based on EN 15459:2007 (the old version of EN15459-1:2017) [412]. Cost optimal level means the energy performance level which leads to the lowest cost during the estimated economic lifecycle, where the lowest cost is determined by taking into account energy – related investment costs, maintenance and operating costs including energy costs and saving.

The literature shows a broad variation of economic evaluation methods for LCC analysis. They all have their advantages and disadvantages. The methods have been formed for different purposes and the user should be aware of their limitations. The relevant literature as assessed and reviewed by Schade [413] is included here as Table 8.1. The table illustrates the six main economic evaluation methods for LCC, their advantages and disadvantages and the purposes they can be used for. From this, it becomes apparent that the most suitable approach for LCC in the construction industry is the net present value (NPV) method.

Table 8.1. The advantages and disadvantages of economic evaluation methods for LCC [413].

| Method | What does it calculate | Advantage | Disadvantage | Usable for |
|---|---|---|---|---|
| **Simple payback** | Calculate the time required to return the initial investment. The investment with the shortest pay-back time is the most profitable one (Flanagan et al., 1989). | Quick and easy calculation. Result easy to interpret (Flanagan et al., 1989). | Does not take inflation, interest or cash flow into account (Öberg, 2005, Flanagan et al., 1989). | Rough estimation if the investment is profitable (Flanagan et al., 1989). |
| **Discount payback method (DPP)** | Basically the same as the simple payback method, it just takes the time value into account (Flanagan et al., 1989). | Takes the time value of money into account (Flanagan et al., 1989). | Ignores all cash flow outside the payback period (Flanagan et al., 1989) | Should be only used as a screening devise not as a decision advice (Flanagan et al., 1989). |
| **Net present value (NPV)** | NPV is the result of the application of discount factors, based on a required rate of return to each years projected cash flow, both in and out, so that the cash flows are discounted to present value. In general if the NPV is positive it is worth while investing (Smullen and Hand, 2005). But as in LCC the focuses is one cost rather than on income the usual practice is to treat cost as positive and income as negative. Consequently the best choice between tow competing alternatives is the one with minimum NPV (Kishk et al., 2003). | Takes the time value of money into account. Generates the return equal to the market rate of interest. It use all available data (Flanagan et al., 1989). | Not usable when the comparing alternatives have different life length. Not easy to interpret (Kishk et al., 2003). | Most LCC models utilize the NPV method (Kishk et al., 2003). Not usable if the alternatives have different life length (Flanagan et al., 1989). |
| **Equivalent annual cost (ECA)** | This method express the one time NPV of an alternative as a uniform equivalent annual cost, for that it take the factor present worth of annuity into account (Kishk et al., 2003). | Different alternatives with different lifes length can be compared (ISO, 2004). | Just gives an average number. It does not indicate the actual coast during each year of the LCC (ISO, 2004). | Comparing different alternatives with different life's length (ISO, 2004). |
| **Internal rate of return (IRR)** | The IRR is a discounted cash flow criterion which determines an average rate of return by reference to the condition that the values be reduced to zero at the initial point of time (Moles and Terry, 1997). It is possible to calculate the test discount rate that will generate an NPV of zero. The alternative with the highest IRR is the best alternative (ISO, 2004) | Result get presented in percent which gives an obvious interpretation (Flanagan et al., 1989). | Calculations need a trail and error procedure. IRR can be just calculated if the investments will generate an income (Flanagan et al., 1989). | Can be only use if the investments will generate an income which is not always the case in the construction industry(Kishk et al., 2003). |
| **Net saving (NS)** | The NS is calculated as the difference between the present worth of the income generated by an investment and the amounted invested. The alternative with the highest net saving is the best (Kishk et al., 2003). | Easily understood investment appraisal technique (Kishk et al., 2003). | NS can be only use if the investment generates an income (Kishk et al., 2003). | Can be used to compare investment options (ISO, 2004). But just if the investment generates an income (Kishk et al., 2003). |

The NPV method is commonly used for products with a long lifespan, where most of the costs occur in the years after the initial investment [413]. The time value of money is being considered, because for example 1000 Euro today will not have the same value as 1000 Euro in ten years from now. This is caused by several economic factors such as inflation, opportunity costs and other changes in the market. To make costs occurring at different time periods comparable, it is necessary to convert future costs into their equivalent in present time. The conversion rate for calculating the present value is the interest rate or discount rate. It considers the important economic factors and represents the future development of prices in the market.

$$PV = \frac{FV}{(1+i)^n} \quad \text{(Eq.8.1)}$$

Where

*PV:* present value [Euro]

*FV:* future value [Euro]

*i:* discount rate [%]

*n:* time period [year]

The net present value furthermore includes the initial investment costs in period 0 as well as the difference in incomes and costs, also known as cash flow, for each time period separately. The sum of the present values of all periods leads to the final formula for NPV[63]:

$$NPV = -Co + \sum_{t=1}^{n} \frac{C_n}{(1+i)^t} \quad \text{(Eq.8.2)}$$

*NPV:* net present value [Euro]

$C_o$: initial investment costs [Euro]

*n:* total amount of periods [year]

$C_n$: cash flow in period [Euro]

*i:* discount rate [%]

*t:* time period [year]

The most cost-effective option is the one with the highest NPV. In case no income occurs the results will be negative. It means that the NPV closest to zero will be the best option. Initial investment costs and cash-in and cash-out factors can be numerous and vary depending on the project. For the building sector, it can however always be broken down into following aspects:

$$C_n = maintenance\ costs + energy\ costs + repair\ \&\ replacement\ costs + recyle\ costs \quad \text{(Eq.8.3)}$$

$C_n$: cash flow in period [Euro]

$$C_0 = manufacturing\ price + installation\ costs + sales\ tax + retail\ markups \quad \text{(Eq.8.4)}$$

$C_0$: initial investment costs [Euro]

The single cost factors listed in Equations (8.3) and (8.4) can be split up even more into their origins and adapted further depending on the product.

Life cycle cost represents the cumulative cost expressed in present value over the period of analysis.

The calculation of global cost (or LLCA) requires, for each energy efficiency measure, the initial investment, the sum of the annual costs for every year (including the operational energy costs) and the final value, all with reference to the starting year of the calculation period. The EU Delegrated Regulation defines the global cost for the macroeconomic calculation as in the following equation:

$$C_g(\tau) = c_I + \sum_j \left[ \sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i) + C_{c,i}(j) - V_{f,\tau}(j) \right] \quad \text{(Eq. 8.5)}$$

Where

- $\tau$*:* calculation period;
- $C_g(\tau)$*:* global cost (referring to the starting year) over the calculation period;
- $C_I$*:* initial investment costs for the energy efficiency measure or set of measures j;
- $C_{a,i}(j)$*:* annual cost during the year I for measure or set of measures j (including running costs and replacement costs);
- $C_{c,i}(j)$*:* annual cost of greenhouse gas emissions;
- $V_{f,\tau}(j)$*:* residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year);
- $R_d(i)$*:* discount factor of year.

In the following section, the annual costs are the sum of maintenance costs, operational costs, energy cost and replacement cost.

Moreover, the discount factor $R_d$ depends on the real interest rate ($R_r$, %) and on the time of the considered cost. It can be calculated according to Equation (8.6), where *p* is the number of years form the starting period.

$$R_d(i) = \left( \frac{1}{1+R_r} \right)^p \quad \text{(Eq. 8.6)}$$

The data requirements according to the reviewed literature for carrying out LCC analysis are categorised in Figure 8.1. These different data influence the LCC in different stages of the life cycle.

The occupancy and physical data could be seen as the key factors in the early design stage. LCC estimation in this stage depends on data such as floor area and the requirements for the building. Flanagan et al. [407] stressed the importance of occupancy data as other key factors, especially for public buildings. Performance and quality data are also influenced by policy decisions such as how well it should be maintained and the degree of cleanliness demanded [414]. Quality data are highly subjective and less readily accountable than cost data [407]. In the more detailed design stage, life cycle cost estimation is based more on performance and cost data of a building [415]. Cost data are most essential for LCC research. However, cost data that are not complemented by other data types would be almost meaningless [407]. These data need to be seen in the context of other data categories to obtain a correct interpretation of them [414].

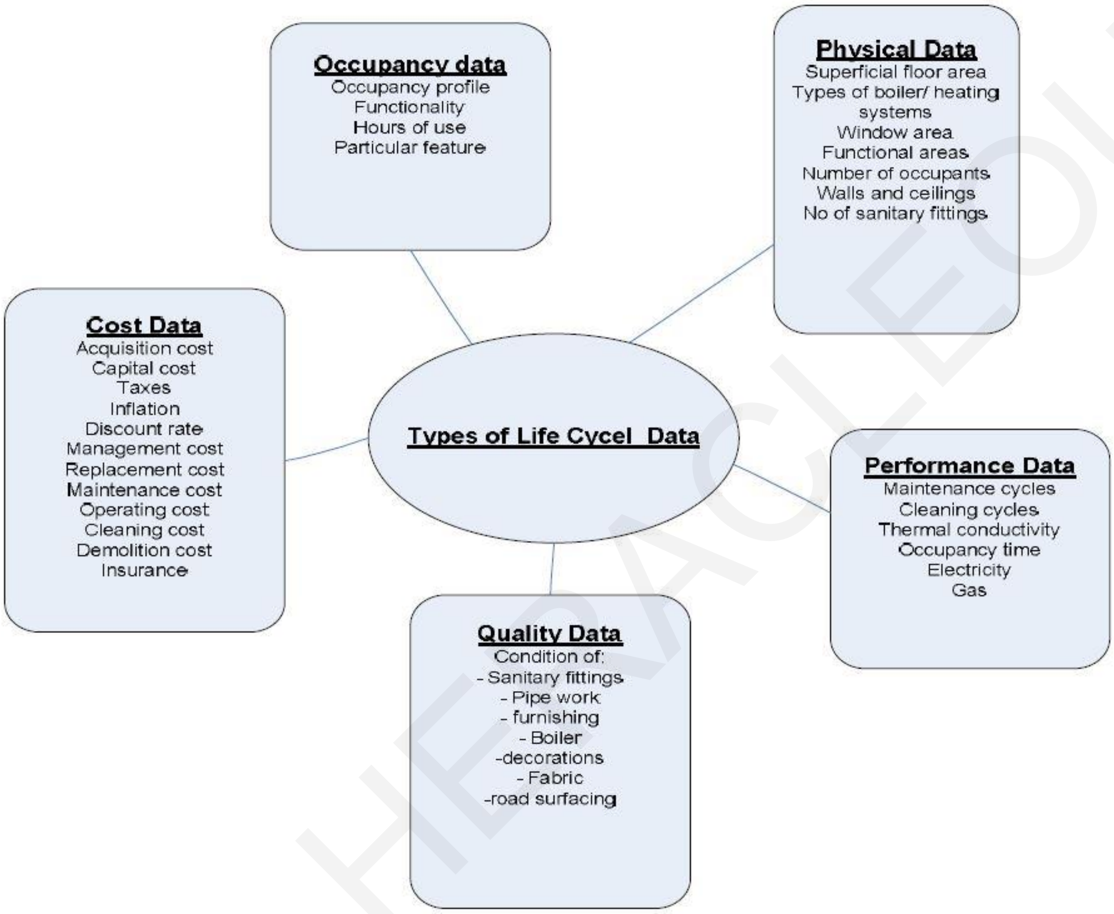



Figure 8.1. The required data categories for a life cycle cost analysis [413].

There are three main sources for data for LCC calculation, i.e. (i) from the manufacturers, suppliers, contractors and testing specialists, (ii) historical data; and (iii) data from modelling techniques.

Data from manufacturers, suppliers, contractors and testing specialists can often be seen as a best guess. They may have a detailed knowledge of the performance and characteristics of their material and components, but do not have knowledge of the ways in which facilities are used [416]. However, extensive knowledge and experience of specialist manufacturers and suppliers are a valuable source for life cycle information. If the required data are not available, modelling techniques can be used. Mathematical models can be developed for analysing costs and statistical techniques can be incorporated to address the uncertainties [416]. Data from existing buildings are used as historical data. Some of them are published as the BMI (Building Maintenance Information) occupancy cost. Other sources include clients' and surveyors' records, and journal papers [407]. Thus, data collection bares some difficulties; however, LCC analysis is only accurate if the collected data are reliable [417].

## 8.4. Sensitivity Analysis

The sensitivity analysis is a useful tool to analyze single assumptions on key parameters of which the future development can have significant impact on the result. The Regulation requires Member States of the EU to perform at least a sensitivity analysis on different price scenarios for all energy carriers of relevance in a national context, plus at least two scenarios each for the discount rates to be used for the macroeconomic and financial cost optimum calculations. The higher the sensitivity the more risk can be attributed to the assumptions on which the input is based. For the deviation of the assumed value, a certain range will be defined in which the input variable can vary. To keep it realistic, the range is based on historical experiences.

## 8.5. Previous study using Life Cycle Costing

Several studies introduced the cost-optimal methodology for the assessment of retrofit approaches in buildings. Kurnitski et al. [418] studied the correlation between cost-optimal levels and nearly Zero Energy Building (nZEB), for Estonian detached houses. Similarly, Hamdy et al. [419] applied the methodology to find the cost-optimal and the energy performance levels of nZEB for a single-family house in Finland. Various options of thermo-physics of the building envelope, heat-recovery units, heating/cooling systems as well as various sizes of thermal and photovoltaic solar systems have been investigated as design alternatives via a three-stage process of optimization. Corrado et al. [420] presented a methodology for identifying the cost-optimal levels for the Italian residential building stock. Again with reference to the Italian climate, Tagliabue et al. [421] applied the cost-optimal methodology to compare three technical systems for replacing an oil boiler after a whole refurbishment of an apartment in Milan. For office buildings, Ganic¸ and Yilmaz [422] have investigated the validity of the global cost calculation periods given in the EU method, under the boundary conditions of Turkey. Some authors have underlined that most of these applications concern a limited number of design options. Therefore, Ferrara et al. [423] have proposed the combination of TRNSYS and GenOpt (a Generic Optimization program) to find the cost-optimal solution for the French single-family building typology, by considering a large number of building configurations. With the same aim, Ascione et al. [424] have proposed an optimization procedure through the coupling of EnergyPlus and MATLAB®, in which a genetic algorithm is implemented.

Wang and Holmberg [425] design an approach to design and assess energy demand retrofitting scenarios of existing Swedish residential buildings and to evaluate of their long-term cost effectiveness using Life Cycle Cost Analysis. Hong, Kim and Koo integrated life cycle cost (LCC) and environmental impact ($LCCO_2$) into Chinese retrofitting strategy assessment. Paiho, Abdurafikov, and Hoang [426]designed cost analysis-based retrofitting strategies to implement building installation system renovations (considering both energy demand and supply) for Russian residential buildings, which further extended the scenario to building district levels.

Zachariadis et al. [427] determined the cost-effective energy efficiency measures in residential buildings of Cyprus with the aid of multiple indices such as weighted effort in investment cost, nominal index of total investment, payback period and net present value. The study came up with a proposal for prioritising specific energy investments such as the installation of heat pumps, insulation of roofs, and replacement of lighting and equipment and then addressed the weaknesses of current regulatory energy efficiency policies in Cyprus. Ziogou et al. [428] investigated the energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings in a warm Mediterranean region i.e. Cyprus. The study revealed that primary energy consumption was reduced up to 25% in heating and up to 20% in cooling operation, while the economic analysis showed that green roof technology is still not cost-effective enough to be implemented in the selected type of office building. Finally, Loukaidou, Michopoulos and Zachariadis [429] examined the cost-optimal analysis of building envelope characteristics in the climatic conditions of Cyprus in order to achieve zero energy buildings and found that the cost-optimal energy performance levels of reference test-cell building are considerably higher than the national minimum requirements.

## 8.6. Chapter summary

This chapter describes the life cycle costing, economic methods and their advantage and disadvantages, of which, as it was demonstrated, net present value is the most common measure. The chapter shows the different data that influence the LCC at different stages of the life cycle and demonstrated the importance of sensitivity analysis in LCCA.

# PART B. RESEARCH METHODS

The Part B presents the research methods employed to address the research questions on the naturally ventilated educational buildings in Cyprus. This section will examine the geographical location and climate of Cyprus, the general background of educational buildings in Cyprus, and explain the methodological pathways to assess thermal comfort, air quality, natural lighting and finally evaluate proposed adaptation measures under current and future climatic conditions in a holistic approach.

# Chapter 9. Geographical location and climate of Cyprus

Cyprus has an intense Mediterranean climate characterized by hot dry summers from mid-May to mid-September and rainy, rather unpredicted winters from November to mid-March, separated by short autumn and spring seasons of rapid change in weather conditions [430]. Based on the Koppen-Geiger Climate Classification (KGCC) [431], Cyprus is divided into two main climatic zones. The first one which is the largest is categorized as Csa, i.e. warm temperate with hot and dry summers, and comprises the central, southern and western and partly northern regions of the island; while the eastern region along with Karpass Penisnsula and the remaining northern areas are included in the other climatic zone described as BSh, i.e. hot semi-arid capital Nicosia, along with Limassol and Paphos, located in the central, southern, and southwestern parts of the island respectively, and are characterized by the Csa climatic features. Larnaca is situated in the southeastern part of the island and belongs to the second climatic zone.

Although a small island, Cyprus features four distinct climatic zones. These are mountainous regions, semi-mountainous, inland plains and coastal areas. Nicosia is largely characterized by inland conditions, with mountainous and semi-mountainous regions (Figure 9.1). The coastal land of Nicosia is largely under military occupation, therefore not taken into consideration at this time. Paphos and Limassol include coastal, semi-mountainous and mountainous domains, whereas Larnaca and Famagusta are mostly coastal with limited inland areas.

Altitude lowers **temperatures** by about 5 °C per 1,000 metres and the presence of sea offers cooler summers and warmer winters near most of the coastline [430]. There is a considerable seasonal difference between summer and winter temperatures, at 18°C inland and about 14°C on the coasts. As for the day maximum and minimum temperatures, in inland areas the difference ranges from 8-10 °C and coastally this lowers to 5-6 °C, in the winter. The difference is more pronounced in the summer, where inland areas experience a min-max difference of 16 °C and other areas between 9-12 °C. At times, inland regions have approximately 10°C higher temperatures than mountainous regions in the summer months. Respectively for winter, inland areas have about 5 °C warmer climate than mountainous regions, on average [430]. Relative humidity also varies among different climate zones, often reflecting temperature patterns, with coastal regions experiencing higher humidity than inland and mountainous regions [432].

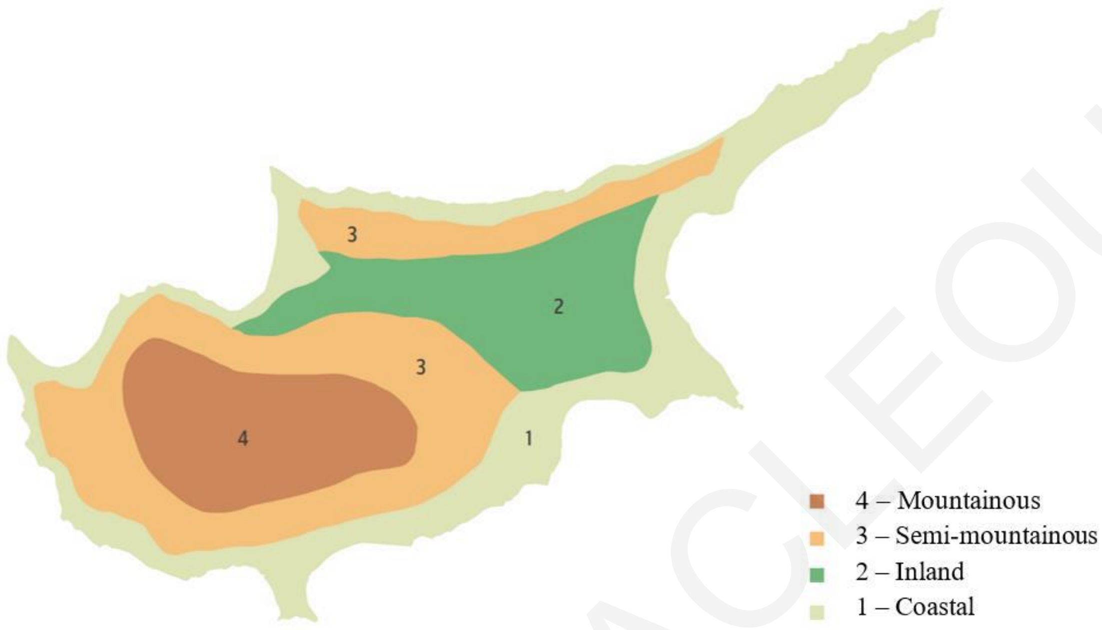



Figure 9.1. Climatic zones of Cyprus [433].

In summer, **rainfall** is almost negligible but isolated thunderstorms sometimes occur which give rainfall amounting to less than 5% of the total in the average year. In winter, Cyprus is near the track of fairly frequent small depressions which give periods of disturbed weather usually lasting from one to three days and produce most of the annual precipitation, the average fall from December to February being about 60% of the annual total.

The average annual total **precipitation** increases up the south-western windward slopes from 450 millimetres to nearly 1,100 millimetres at the top of the central massif. On the leeward slopes amounts decrease steadily northwards and eastwards to between 300 and 350 millimetres in the central plain and the flat south-eastern parts of the island.

**Snow** falls rarely in the lowlands but falls frequently every winter on ground above 1000 meters usually starting on the first week in December and ending in the middle of April. Although snow cover is not continuous during the coldest months it may lie to considerable depths for several weeks especially on the northern slopes of high mountainous Troodos.

Seasonal change in mean **soil temperatures** is from about 10 °C in January to 33 °C in July at 10 centimetres depth and from 14 °C to 28 °C at one metre. On the mountains at 1,000 metres above sea level these mean seasonal values are lowered by about 5 °C. Absorption of large amounts of solar energy during the day and high radiation losses under clear skies at night cause a wide daily range of soil temperatures in summer. At the soil surface, the daily variation on a typical July day in the lowlands is between 15 °C near dawn to near 60 °C in middle of the afternoon. At only 5 centimetres depth the variation is reduced to between 24 and 42 °C and at 50 centimetres, depth there is no daily temperature change.

As Cyprus is an island, the coastal areas are affected by the **relative humidity** which to a large extent is a reflection of temperature difference. Humidity may be described as average or slightly low at 65 to 95% during winter days and at night throughout the year. Near midday in summer it is very low with values on the central plain usually a little over 30% and occasionally as low as 15%.

Cyprus experiences a very sunny climate compared to most counties. In the central plain and eastern lowlands, the average number of hours of bright **sunshine** for the whole year is 75% of the time when the sun is above the horizon. Over the whole summer six months there is an average of 11.5 hours of bright sunshine per day whilst in winter this is reduced only to 5.5 hours in the cloudiest months, December and January. Even on the high mountains the cloudiest winter months have an average of nearly 4 hours bright sunshine per day and in June and July the figure reaches 11 hours.

In the eastern Mediterranean region, **winds** are mostly westerly or south-westerly in winter and north-westerly or northerly in summer. Over the island of Cyprus however, winds are quite variable in direction with orography and local heating effects playing a large part in the determination of local wind direction and strength.

The climate of Cyprus can be described through the analysis of the 4 climatic zones (Figure 9.1) for the period of 1999 to 2005.

Considering **climatic zone 1**, the coastal area of Polis has been selected as a case study for analysis. Polis is a small town at the north-west end of the island of Cyprus, at the centre of Chrysochous Bay, and on the edge of the Akamas peninsula nature reserve. The position of the location is determined by the coordinates 35°2′0″N and 32°26′0″E at an altitude of 15 m above sea level. The mean daily maximum temperature during July is 33.5°C while the mean daily minimum temperature is 21.6 °C. The extreme maximum is observed at 40.8°C. For the same period, the mean relative humidity is 57% at 08:00 and 55% at 13:00.

The mean daily maximum temperature during February is 16.3°C while the mean daily minimum temperature is 7.3°C. The extreme minimum during January is observed at -2°C. For the same period, the mean relative humidity is 74% at 08:00 and 59% at 13:00.

The mean annual rainfall in the area of Polis is at 474mm. The most important rainfall is observed from November to March, while in the remaining months, the rainfall does not exceed 5% of the mean annual rainfall.

Regarding **climatic zone 2**, the lowland area of Athalassa in Aglantzia has been selected for analysis. Aglantzia is a suburb and a municipality of Nicosia. The position of the location is determined by the coordinates 35.14592°N and 33.390169°E at an altitude of 162m above sea level. The mean daily maximum temperature during July is 37.2°C while the mean daily minimum temperature is 22.2 °C.

The extreme maximum is observed at 43.4 °C. For the same period, the mean relative humidity is 50% at 08:00 and 27% at 13:00.

The mean daily maximum temperature during February is 15.9°C while the mean daily minimum temperature is 5.2°C. The extreme minimum during February is observed at -2.9 °C. For the same period, the mean relative humidity is 82% at 08:00 and 54% at 13:00.

The mean annual rainfall in the area of Athalassa is at 342.2 mm. The most important rainfall is observed from November to March, while in the remaining months, rainfall does not exceed 5% of the mean annual rainfall.

For the examination of **climatic zone 3**, the semi-mountainous area of Mallia has been selected for analysis. Malia is a village in the Limassol District of Cyprus, located 4 km south of mountainous Omodos. The village is located south of the Troodos wine region almost thirty km northwest of the city of Limassol. The position of the location is determined by the coordinates 34°48′59″N and 32°46′58″E at an altitude of 669 m above sea level. The mean daily maximum temperature during July is 32.6°C while the mean daily minimum temperature is 19.7 °C. The extreme maximum is observed at 35.9 °C. For the same period, the mean relative humidity is 66% at 08:00 and 25% at 13:00.

The mean daily maximum temperature during February is 15.8°C while the mean daily minimum temperature is 5.9°C. The extreme minimum during February is observed at 1.1 °C. For the same period, the mean relative humidity is 84% at 08:00 and 41% at 13:00.

The mean annual rainfall in the area of Malia is at 660 mm. The most important rainfall is observed from November to March, while in the remaining months, the rainfall does not exceed 5% of the mean annual rainfall.

**Climatic zone 4**, is analysed through the case of the mountainous area of Prodromos. Prodromos is the highest village in Cyprus at 1,380 metres above sea level and is determined by the coordinates 34°56′54″N and 32°49′46″E. The mean daily maximum temperature during July is 28.1 °C while the mean daily minimum temperature is 18.4 °C. The extreme maximum is observed at 35.4 °C. For the same period, the mean relative humidity is 34% at 08:00 and 38% at 13:00.

The mean daily maximum temperature during February is 6.6°C while the mean daily minimum temperature is 0.3 °C. The extreme minimum during January is observed at -10.2 °C. For the same period, the mean relative humidity is 78% at 08:00 and 76% at 13:00.

The mean annual rainfall in the area of Prodromos is at 790.1 mm. The most important rainfall is observed from October to April, while in the remaining months, the rainfall does not exceed 5% of the mean annual rainfall.

An **outdoor weather station** was installed on the roof of the case study building, at a height of 10m above street level, i.e. 4 metres above the regular height of buildings found in the immediate vicinity. For the confirmation of the climatic data of the study area (climatic zone 2) and for the recording of the microclimate of the case study, the outdoor conditions including temperature, humidity, wind speed, solar radiation and precipitation were recorded for the whole duration of the study. The specifications of the measurement instruments are summarised in Table 10.4. The recorded values from the extreme months based on the outdoor weather station, are summarized below, showing some small variations compared to the typical meteorological year. Specifically, slightly lower temperatures are observed during the warm month and slightly higher temperatures during the cold months. The mean daily maximum temperature during July was 36.6°C while the mean daily minimum temperature was 24.7 °C. The extreme maximum was observed at 40.1 °C. For the same period, the mean relative humidity was 80% at 08:00 and 29% at 13:00.

Indicatively, the mean daily maximum temperature during February is 18.2°C while the mean daily minimum temperature is 10.1°C. The extreme minimum during February is usually observed at 7.1°C. For the same period, the mean relative humidity is 89% at 08:00 and 55% at 13:00.

# Chapter 10. Educational buildings in Cyprus

## 10.1. Introduction

The chapter aims to traces the relation between the organisational structure of the Cypriot educational system diachronically from the beginning of its operations, the time of operation throughout the year and the day and analyse the representative types of the school buildings. Moreover, the chapter explains the methodologies and criteria for the selection of buildings under study for the needs of this thesis and describes the characteristics of educational buildings in terms of structure, geometry, construction and technical systems. Finally, a chapter summary is provided.

## 10.2. The structure of the educational system

Public education in Cyprus is free and accessible to all at three levels, primary education, general secondary, technical and vocational education, and higher education.

**Primary education** is the first stage of education and has as its main goal to organize, secure and offer to all children - regardless of gender, country of origin, social background and intellectual abilities - such opportunities to develop in a balanced way the cognitive, emotional and psychomotor abilities. Primary education refers to compulsory six-year education and is provided to students aged six to twelve years old [434].

**Public secondary general education** is provided to students aged 12 to 18, through two three-year rounds of courses - Gymnasium and Lyceum. The two cycles include curricula offering interdisciplinary (Health Education, Environmental Education, etc.), as well as various extracurricular activities (groups, educational trips, visits, etc.), in order to achieve a holistic and balanced development of students' personalities. Attendance is compulsory until the age of 15 or the completion of Gymnasium, whichever comes first [434].

**Secondary Technical and Vocational Education** is secondary level education provided to students aged 15 to 18, through a three-year course. It offers two streams of education, theoretical and practical, which respectively aim through the offer of a balanced program of general education and technological-laboratory specialization, to prepare graduating students for direct employment in the industry, or for the continuation of their academic career in Higher Education Institutions [434].

The **Higher Education** Institutions of Cyprus consist of Public Universities, Private Universities, Public Higher Education Schools and Private Higher Education Schools.

Public Higher education in Cyprus includes three public universities with significant research and educational contribution. The University of Cyprus (UCY) was founded in 1989 and accepted its first students in 1992. It is a rapidly growing educational and research institution that aims to meet the social, educational and other goals of the Republic of Cyprus [434].

The Open University of Cyprus (OUC) is a state higher education institution that provides undergraduate and postgraduate programs, utilising open and distance education. It was founded in 2001 and admitted its first students in 2006.

The Cyprus University of Technology (CUT) was founded in 2004 and admitted the first students in 2007. It includes in an upgraded form, the cognitive subjects of the public schools of higher education, Higher Technological Institute (ATI), Nursing School and Higher Hotel Institute of Cyprus with the possibility of development new faculties and departments [434].

It would be interesting to mention that there are also private educational institutions in Cyprus covering all levels of education but this thesis focuses on public because of the sheer great number of them, as well as their standardised design principles according to which they are being constructed.

## 10.3. Time of operation of school building

Primary and secondary schools operate about 10 months a year, from early September to mid-June, with a fortnightly holiday season at Christmas and Easter respectively. Primary education has operating hours from 07:45 to 13:05 while secondary education, from 07:30 to 13:35.

The timetable includes 35 teaching sessions per week, which are distributed every 7 of the 5 operating days of the schools. The teaching periods last 40 minutes in primary education and 45 minutes in secondary education. The breaks between the second - third period, fourth - fifth and sixth - seventh duration are 20, 10, 10 minutes respectively in primary education and 20, 20 and 10 minutes respectively in secondary education [434].

The implementation of the unified all-day school in primary education provides for operating hours from 07:45 to 16:00. The teaching periods amount to a total of 47, compared to 35 periods. Indicatively, by the school year 2019 - 20 the all-day school had already been implemented in 137 primary schools out of a total of 331 that operated in the same school year [435].

## 10.4. Occupancy of classrooms

The classroom has an occupancy profile of 20-25 students on weekdays from 07:30 to 13:35 with 3 small breaks; however, in some cases, students are moved during the day to other laboratory or physical education rooms to engage in other activities. This corresponds to a functional area of 2.5 $m^2$ per person. It is noted that some classrooms are also used in the afternoon for extracurricular activities (14:45-18:00) by a smaller number of occupants, i.e., 6-8 in each classroom.

## 10.5. Representative types of school buildings

The Technical Services of the Ministry of Education, Culture, Sports and Youth are responsible for ensuring the necessary building infrastructure for the operation of public education. During the school year 2018-2019, 272 kindergartens, 331 primary schools and 134 high schools were in operation.

The overall curriculum needs of Public Education refer to the logistical infrastructure of school buildings and mobile equipment. Specifically, these needs include the construction of new school buildings, the expansion of existing school units and the general improvement of existing buildings and sports infrastructure. Extension and improvement projects include the addition of general classrooms, laboratories and the construction of multipurpose halls, as well as a functional redesigning of the existing building capacity to meet the detailed training programs and the approved new development building programs. The gradual seismic study and reinforcement of the load-bearing structure of school buildings is an important part of the program for upgrading the existing logistical infrastructure.

In addition to the categorization of educational buildings depending on the level of education they host, in buildings of pre-primary, primary, secondary and high school education, another criterion of categorization is the time of construction of the buildings and consequently their morphological and structural elements.

Based on these criteria, four categories of buildings are distinguished:

a) school buildings built during the Ottoman and British occupation,
b) school buildings designed by important Cypriot architects of modernism,
c) school buildings designed and implemented by the Technical Services of the Ministry of Education, Culture, Sport and Youth after the proclamation of the Republic of Cyprus, and
d) school buildings resulting from architectural competitions and commissions to independent architects.

### *10.5.1. School buildings built during the Ottoman and British occupation*

The close ties with Greece and the financial and cultural support of the rich and powerful religious institutions, placed schools at the center of the ethnocentric atmosphere of the time. Especially in the case of the Greek-Cypriot community who saw British rule as an opportunity to de-Ottomanize the island and unite with the newly formed Greek state, school buildings (from urban high schools to rural primary schools) became a privileged place for experimentation of neoclassicism, which is codified and projected as an ethnocentric image in public space[436]–[439].

The design of school buildings at the beginning of the 20$^{th}$ century, followed the general neoclassical character of other public buildings of the period, adapted to the data of Cyprus mainly through the use of local materials. Most of these buildings use limestone as the main building material, they are single-storey or two-storey and are organized linearly or in a "Π" shape. The typology is characterized by the concentration of all the functions of the school building in a compact-introverted building volume, the symmetrical organization of the floor plan and the neoclassical elements of the façades. These schools meant to convey the “Greekness” through the aesthetic choice of a neoclassical vocabulary [38].

Representative examples of schools of this period are the School for Girls of Faneromeni, (1859) and the Pancyprian Gymnasium, both within the walls of Nicosia (1893).

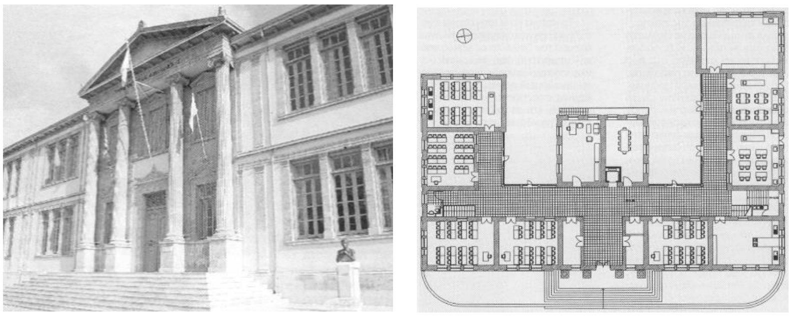


Figure 10.1. School for Girls of Faneromeni, within the walls of Nicosia [38].

### *10.5.2. School buildings designed according to the principles of the modern movement*

The introduction of the ideas and principles of the modern movement in the school architecture of Cyprus, especially from the 60's, brought about the reversal of the previous design principles. Based on Pyla and Phokaides [437], modernism was used as an aesthetic choice initially made during the British rule, but especially after the independence of Cyprus in 1960 in order to embody the modernising effects of the new state and move away from ethnically-charged aesthetic choices like the neoclassical elements, but to utilize a more “international style”. The predominance of the use of reinforced concrete and modern construction methods led to the production of a significant number of school buildings designed by Cypriot architects, the majority of which are distinguished for their modern spirit, architectural completeness and coherence [440].

The local construction aspects of modernism, in direct relation to the climatically rational design, were the main model for the development of educational architecture in Cyprus. In its architectural conception, the school building is introduced as a system of linear building elements that allow the application of a series of bioclimatic design strategies, which refer to solar gain, sun protection, passive cooling and the use of natural light. A significant element is the horizontal or vertical awnings that compose the façades. This period presents remarkable examples which are characteristic of the evolution of educational architecture in Cyprus.

Examples of schools of this period are the Pancyprian Gymnasium for Girls of Pallouriotissa, (Nicosia, 1956-62) by Thymopoulos, the Engomi Gymnasium (Nicosia, 1960) by the office Zembylas and Kythreotis, Kykkos A’ Lyceum, (Nicosia, 1960-63) Commercial Gymnasium of Nicosia (1962) by the office of Iacovou and Andrea Philippou, and the Primary school of Dasoupolis (Nicosia 1964-65) by Pefkios Georgiades.

Figure 10.2. Pancyprian Gymnasium for Girls Pallouriotissa, Nicosia, 1956-62, architect Dimitris Thymopoulos [38].

### *10.5.3. School buildings designed by the Technical Services of the Ministry of Education, Culture, Sport and Youth*

The majority of school buildings in Cyprus still operating today, are the result of the design of the Technical Services of the Ministry of Education, Culture, Sports and Youth. A large number of typical school buildings were erected in the years following the Turkish invasion of 1974 and subsequent occupation of 38% of the island, to meet the building needs that arose.

The typology of modern architecture still governed the design approach of school buildings of this category, except minor deviations. They are two-storey buildings, rarely three-storey, characterized by strong standardization in their design and construction. The layout of the functional spaces along open corridors is the most intense feature of the typological organization of the typical school buildings. These provisions are combined to create a system of linear building elements, with the existence of closed courtyards in the form of atriums, open courtyards on one or both sides and free elements. This system allows the building to be fully adapted to the available plot and favors additions to the building program by expanding or adding new classrooms. However, the architectural design of the school building arises without substantial concerns regarding the climatically rational design, the topographical height defferences, the appropriate orientation of the building volumes and the arrangement of the openings in relation to the prevailing winds.

Examples of schools of this period are Primary School of Pernera Strovolos, (Nicosia, 1990), Secondary School of Stavrou Strovolou (Nicosia 1992), High School Ayios Georgios, Lakatameia (Nicosia 1999).

Figure 10.3. Secondary School of Stavrou Strovolou (Nicosia 1992), Technical Services of the Ministry of Education, Culture, Sport and Youth.

### *10.5.4. School buildings as a result of architectural competitions and assignments*

The Technical Services of the Ministry of Education, Culture, Sport and Youth are preparing an important development program for the construction of new school buildings, to meet the building needs and to replace existing old school buildings if needed [441]. In recent years, the majority of studies for the design of new school buildings, extensions and upgrades are outsourced to private-practicing architects, either through the tender process of financial and technical proposal, or through a nationwide architectural tender. During the school year 2019-2020, the total number of projects implemented was 70, of total cost € 38,446,607, while 21 new large-scale projects with a budget of € 30,076,060 are planned to start after the start of the new school year and before the end of 2020 [441] The majority of them concerns extensions and upgrades.

The educational buildings that were designed and implemented in recent years through the process of architectural tenders and direct design assignments, use mostly the same building materials, but differ in their architectural conception and morphological expression. The majority of the examples demonstrate the conscious effort of architectural designers to redefine school architecture through proposals that address issues of scale, spatial experience and interactions between structured space and students, as well as the conscious integration of environmental principles into the design [38].

One of these projects was the construction of the new Lyceum of Archbishop Makarios III of Dasoupolis, which took place through a Pancyprian architectural competition and completed in 2014. Another example of this new approach was a project assigned to Theocharis David for the design of the Primary School of Makedonitissa which was completed in 2009.


Figure 10.4. Lyceum of Archbishop Makarios III of Dasoupolis, 3Ds, Architect: Alexandros Livadas [442].

Figure 10.5. Primary School of Makedonitissa, Architect: Theocharis David [443].

## 10.6. Methodologies and criteria for the selection of study buildings for thesis needs

The selection of the appropriate sample of school buildings requires the development of criteria for the selection of the study sample, which will ensure the research requirements of this dissertation.

The **first criterion** is the identification of a **representative type** of building and the majority of the building stock. The majority of educational buildings in Cyprus consists of typical typologies and construction characteristics. For the needs of this particular research, 114 educational buildings of secondary education all over Cyprus were investigated. From the sample under study, 102 educational buildings, i.e. 90.5%, can be categorized as typical school buildings. These buildings were designed and erected by the Technical Services of the Cyprus Ministry of Education and Culture in the late 1970s and early 1980s to meet the needs of educational buildings after the 1974 Turkish invasion.

The **second criterion** of selection are the **common characteristics** of the buildings that allow the generalization of the results. A typical building designed by the Technical Services is characterized by uniformity in terms of typology, morphology and construction. The architectural designs of school buildings show significant similarities, extensive standardization of building components and construction methods.

The **third criterion** is the selection of buildings in a climatic zone that adaptation measures can be generalized in more than one climatic zone. Table 10.1 shows the required climatic reference data for the calculation of the Energy Performance of the building, as regulated by the buildings energy efficiency European Directive 2010/31. The duration of the period of heating and cooling is presented in Table 10.1 and more details can be found in Chapter 9. The table shows that climatic zones 1, 2 and 3 require the same duration for heating and cooling, allowing the generalization of the conclusions that will emerge from the study of these buildings.

Table 10.1. Climate data for each climatic zone [444].

| **Climatic zone** | **Heating degree hours <20 °C** | **Duration of heating period <20$^{0}$C** | | **Duration of cooling period >24$^{o}$ C** | | **Mean ex. Temp. for heating period $^{o}$C** | **Mean ex. Temp. for cooling period $^{o}$C** |
|---|---|---|---|---|---|---|---|
| | | Months | Days | Months | Days | | |
| **C1 - Coastal** | 1049 | 6 | 181 | 4 | 122 | 14.2 | 25.8 |
| **C2 - Inland** | 1231 | 6 | 181 | 4 | 122 | 13.2 | 27.2 |
| **C3 – Semi-mountainous** | 1339 | 6 | 181 | 4 | 122 | 12.6 | 26.0 |
| **C4 – Mountainous** | 2033 | 8 | 242 | 2 | 62 | 11.6 | 25.2 |

The **fourth criterion** is the selection of school buildings that allow for the evaluation of thermal and energy performance in smaller study models with different orientations. Educational buildings are constructed within varied orientations without substantial concerns regarding a climatically rational design. The selection of a building that has linear classrooms with orientations allows the evaluation of thermal and energy performance in a smaller sample.

The **fifth criterion** is the selection of school buildings of secondary level education versus primary school and lyceum. Students at secondary schools are able to respond to field research without requiring excessive simplifications in how to compile a questionnaire compared to primary school students. Moreover, in secondary education, the students work as a group following the same curriculum compared to high school education where each student follows a different curriculum according to their chosen stream of specialization.

### 10.7. Characteristics of the case study building and generally of typical school buildings

According to the criteria developed above, a secondary school in the urban area of Nicosia, Cyprus (latitude 35°10’ N and longitude 33°21’ E) was selected for an in-depth investigation. The school has classrooms with different orientations. The case study used was the **Archbishop Makarios III Secondary School,** which was designed and erected by the Technical Services of the Cyprus Ministry of Education and Culture, in 1984, which is responsible for all school infrastructure in Cyprus. The building is located on a flat plot with an altitude of 170 meters above sea level. The case study is considered as **representative of educational buildings in Cyprus** in terms of typology, morphology and construction and its standard characteristics render it ideal for an analysis of the thermal comfort of educational schools in Cyprus.

In its general composition the school building consists of free linear elements on the east - west and north - south axes (Figure 10.6). This arrangement creates a main central courtyard intended for the main outdoor activities of the school (Figure 10.7). In addition, secondary open spaces are created between the free building volumes. The classrooms are exposed to all orientations.

Figure 10.6. Archbishop Makarios III Secondary School, 1984.

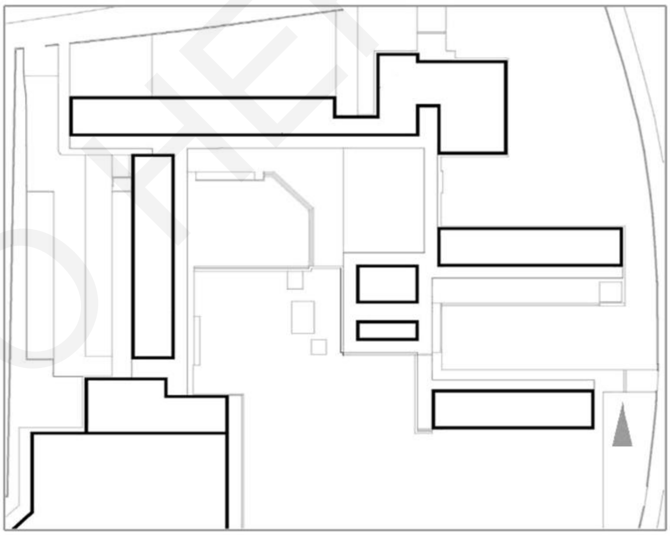


Figure 10.7. Diagrammatic plan of Archbishop Makarios III Secondary School [38].

The satellite image (Figure 10.8) shows the relationship with the road network, the basic building structure of the school building, the relationship of the built space with the outdoor school space (schoolyard and sports facilities) and the wider urban environment.

Figure 10.8. Satellite image of Archbishop Makarios III Secondary School [38].

Below are the main characteristics of both the Archbishop Makarios III Secondary school and the typical school, in terms of organization, function and architectural expression of the built indoor and outdoor space, in addition to the construction and environmental approach of the school complex.

### *10.7.1. Organizational structure of typical school buildings*

The structure of the typical school building is divided into two main sections, the constructed school buildings complex and the outdoor configurations.

The built school complex includes:

- the teaching spaces (general and special classrooms and laboratories);
- the administration and other support areas;
- a multipurpose space; and
- circulation spaces

The outdoor configurations of the school building include:

- the main courtyard;
- secondary courtyards;
- outdoor sport facilities ;
- the garden of the school; and
- the perimetric zone of the school complex with the planting of fencing.

The teaching spaces are divided into general and special classrooms and laboratories. The special classrooms refer to classrooms of art, music, biology, physics, chemistry, home economics, mathematics, languages, computer laboratories and science and technology laboratories and vary in size depending on the field.

The multipurpose space is directly related to the outdoor sports facilities and is intended mainly for conducting the physical education course, while it is rarely a place for school activity and socialization of users. In addition, this space is used for events/celebrations/commemorations and other formal mass school events.

The **organizational structure** of the teaching spaces is perhaps the strongest feature of the organization of typical school buildings. The classrooms are placed along an open corridor, which lengthens linearly. The composition of such linear elements form “Γ”-, “Π”-shaped or closed square layouts (Figure 10.9).


Figure 10.9. Diagrammatic representation, linear classroom layout along a linear open corridor [38].

The linear arrangements of elements are joined together to create a system of linear building elements. The system provides types of courtyards, closed in the form of atriums, open on one or both sides and free elements (Figure 10.13). This system allows the building to be adapted to the available plot, regardless of morphology, and favors additions to the building program by expanding or adding new linear arrangements of classrooms.

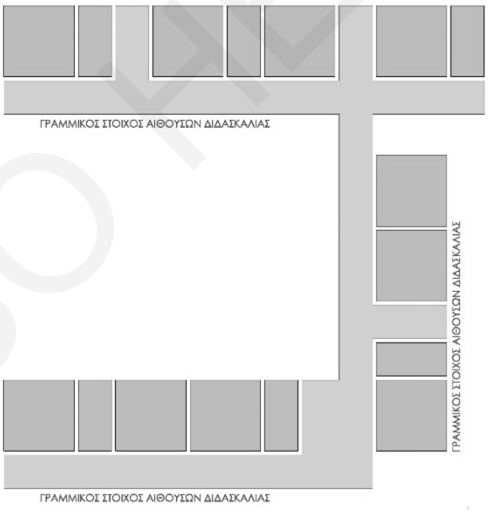



Figure 10.10. Diagrammatic representation, Layout of linear elements and creation of “Γ”, “Π” or square shapes [38].

Generally, indoor connection of classrooms or any way of unification is not anticipated in school structure; therefore, the opportunities for unified educational or non-educational activities are minimized.

Typical school buildings have a clear introverted character and are essentially functionally and visually isolated from the wider environment. The typical layout of secondary schools is structured around inner courtyards creating enclosed layouts. This introversion results in the isolation of school activity, functional and visual, from the actions of the wider environment (Figure 10.14).

Figure 10.11. Introverted layout of a school building.

The existence of clerestories instead of windows on sides not facing the courtyard contributes to this isolation even further, by ensuring every interruption of the visual connection of the school space with the wider built and natural environment.

Figure 10.12. Clerestories of classroom facing the outdoor built environment.

The outdoor area of the school is a vital area of the complex and crucial element of the organization and operation of the school. The main courtyard consists of an atrium with a rectangular or square shape. It is intended for spontaneous break activities, for student gatherings (ceremonies and events) and rarely for educational activities [38]. This is a paved area, with minimal, or in most cases non-existent planting.

In the secondary courtyards, which are mainly created from the compositional development of the typical school building with the parallel or vertical placement of linear building elements, similar activities to those in the main courtyard take place. Yards of this type are most commonly paved with gravel or compacted earth instead of paving tiles.

Outdoor sports facilities include a football field and a basketball/volleyball court and are mainly used for physical education. They are usually isolated from the rest of the school complex and are rarely used for other educational or non-educational activities.

The garden is usually located along the road and in direct relation to the main entrance and the reception areas of the school complex. In most cases, the gardens are intended for landscaping the entrance and the main façade of the school.

The perimeter zone of the school complex includes a metal fence and often a perimeter vegetation that has no educational use and functions exclusively as a buffer zone between the school building and its wider environment, offering isolation and security.

### *10.7.2. Geometrical features, layout and equipment of the main classroom*

The geometrical features, layout and equipment of a typical classroom appear to be the same at different levels of education. Classrooms are **slightly rectangular** and their dimensions are around 7.00×8.00×3.20m (W×L×H) (Figure 9.16). Small differences in size occur depending on the design of each school building; however, the logic of the classroom organization does not differ. The access to the classroom is made by a semi-open (covered) linear corridor 2m wide. The above provisions cannot be justified with some climatic consistency, since they are the same in all orientations (Figure 10.13 and 10.14).

Figure 10.13. The internal configuration of the classroom.

Classrooms have a linear disposition which enables the placement of openings along the two longer sides of the room, i.e. extensive windows on one side and clerestories on the other side. The openings to floor ratio is 25% and the openings to walls ratio is 15%, i.e., 50% of south elevation, 17% of north elevation, while east and west elevations have no openings. It is worth noting that no building or plant elements shade the openings. More specifically, in each classroom, there are six glazed windows on the south side, i.e., C-H, a fixed glazed window on the south side, i.e., B, a semi-glazed door on the south side, i.e., A, four fixed clerestories on the north side, i.e., I, K, L, N, and two openable clerestories, i.e., J and M (Figure 10.14). The classrooms are connected with semi-open corridors, 2m wide, which provide solar protection to all windows. No external shading device is available on the clerestories on the other long side of the classroom.

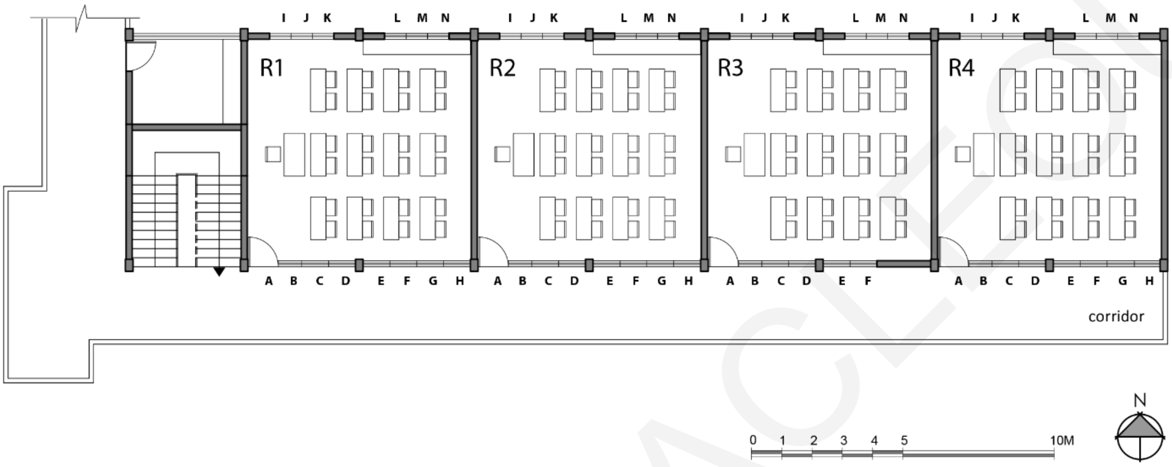



Figure 10.14. Layout plan of a characteristic secondary school classroom in Cyprus. Openings are marked from A to N.

### *10.7.3. Window and curtain operation of classroom*

The behaviour of students concerning **window and curtain operation** of classrooms was recorded through field observation and questionnaires in order to derive reliable results in relation to the students' engagement with the building operation (described in **Chapter 16.2.1** and **Chapter16.3**). Students and teachers used internal black-out curtains to eliminate solar radiation and to avoid glare issues and distraction. Concerning window operation, windows seem to be opened all day during summer occupied hours while the clerestories were rarely opened. During the winter period, windows were rarely opened. When the outdoor temperature felt below 15 °C, few windows were opened but this pattern became more frequent when the outside temperature went above 15 °C. Once windows were opened, they remained open until occupants feel discomfort. Closing a window indicated an act of eliminating environmental discomfort related to indoor temperature. During the intermediate period, windows seems to be opened after the first break time when the temperature is rising.

### *10.7.4. Construction characteristics of educational buildings*

Typical school buildings have a load-bearing structure made of reinforced concrete like most building structures in Cyprus. The structural design of the load-bearing structure of typical school buildings shows regularity and a significant degree of standardization.

The columns of the building are arranged in grids of the order of 7x4m. The classrooms usually consist of two continuous construction grids, resulting to the creation of slightly rectangular classrooms with dimensions of about 7x8m and an area of 50 to 60 $m^2$.

The wall is filled with Cypriot conventional perforated bricks, dimensions 20 x 30 x 10 cm. The total width of the masonry amounts to 25 cm, including the coating. Typical school buildings have no thermal insulation in masonry or load-bearing elements, columns and beams (Figure 10.15).

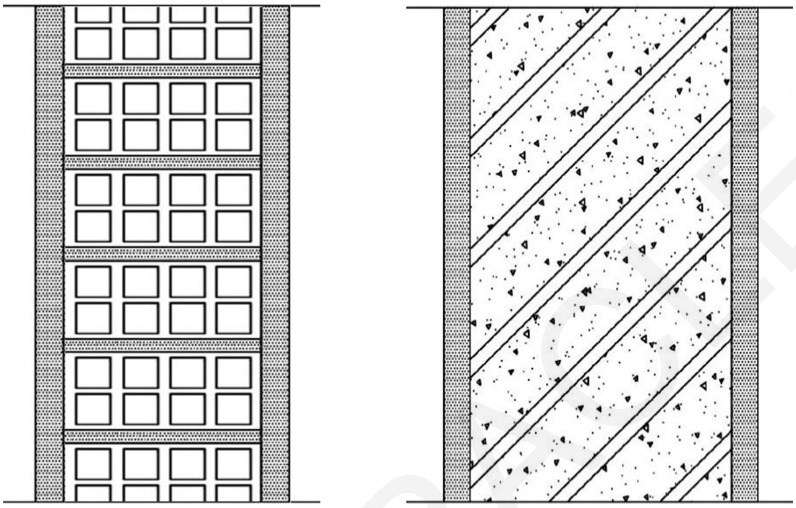


Figure 10.15. Masonry construction detail. Materials from outside to inside: 25 mm cement mortar, 200 mm perforated ceramic brick, 25 mm cement mortar and Reinforced concrete column construction detail. Materials from outside to inside: 25 mm cement mortar, 250 mm reinforced concrete, 25 mm cement mortar [38].

The openings are usually made of aluminium frames, less often with metal ones, while in all cases they have single pane of glass.

The floors of school buildings are mostly paved with prefabricated cast mosaic tiles measuring 40 x 40 cm. The open spaces are paved with concrete paving slabs of dimensions 40 x 40 cm or with compacted soil or gravel, while the basketball/volleyball courts are asphalted. The fences of school buildings consist of a metal railing at a height of usually 1.80m.

The thermal properties of the building components that are typical in the majority of educational buildings that were built before the energy performance requirements of 2007 are summarised in Table 10.2. The values of the typical construction characteristics and materials were calculated according to the “Thermal Insulation Guide” published by the local authority of “Energy Service, Ministry of Energy, Commerce and Industry” [391].

Table 10.2. Construction characteristics and material of a typical school premises in Cyprus.

| Building Elements | Construction Detail | U-Value ($W/m^2K$) | G-value | Effective Thermal Capacity ($KJ/m^2K$) |
|---|---|---|---|---|
| **External Wall** | 200mm single layer of brick and three layers of plaster (20-25mm) | 1.389 | - | 120 |
| **Internal Wall** | 100mm single layer of brick and three layers of plaster (20-25mm) | 1.235 | - | 120 |
| **Roof** | Concrete slab and asphalt layer of 5mm | 3.239 | - | 240 |
| **Ground Floor** | Concrete slab and tiles | 1.6 | - | 232 |
| **Window** | 6mm single glazed and aluminium frame | 6 | 0.82 | - |

**Airtightness** is a significant factor of the energy efficiency and IAQ of a building. In order to determine classroom airtightness, an experimental procedure took place using the fan pressurization method described by ISO 9972:2015 [445]. The test determines the air change rate at a pressure difference of 50 Pa (n50). The accuracy of the pressure channels of the blower door is +/- 1% of reading, or 2 times the resolution, whichever is greater. A test was performed in one classroom (R3). The experiment was performed for the “in use scenario” where nothing was sealed. This includes leakage from neighbouring classrooms that measures internal building leakage corresponding to typical use conditions (method A of ISO 9972:2015). The results show 9.4 air change rate per hour (ach) at a pressure difference of 50 Pa (Figure 10.16). It is worth noting that there is no requested standard for mandatory ventilation rate in Cyprus.

Figure 10.16. Blower door test for the determination of airtightness of the building.

### *10.7.5. Technical support systems*

Typical school buildings have a central heating system with a diesel-heated boiler between 07:00-10:00 every weekday and 14:45-17:45 on Monday, Tuesday, Thursday and Friday in some schools where afternoon activities take place. The heating of the functional spaces is achieved by the use of hot water radiators. Although there is no cooling system in the classrooms for the summer season until today, it is noted that in classrooms with special operating conditions, special needs and special cases of users, air conditioners are already installed (in the offices of the Director, in the secretarial offices, in the teachers' lounge, doctor's office, amphitheaters, event halls, summer school laboratories, Special Education Units and other special classrooms). They have hot water for use from an electric water heater, in selected laboratories, the doctor's office and the canteen.

The artificial lighting of the classrooms is ensured by the installation of fluorescent lamps, 65W, and two per construction grid. In the new school buildings, but also in the existing ones, a structured cabling system and provision for photovoltaic systems of electricity generation are provided.

### *10.7.6. Environmental approach of educational buildings*

The school premises offers possibilities of application of bioclimatic design principles due to the building volume configurations as well as the open structure of the buildings. The placement of the building volume on the east-west axis and with the covered corridor to the south, ensures direct solar gains during the heating period, adequate sun protection of the glazing, and cross ventilation during the cooling period. In addition, as a result of the existence of openings along the two sides of the classrooms, the possibility of utilizing natural light is provided.

However, although the educational buildings have the potential for application of bioclimatic design, it is found that the architectural design of the school building at the level of organizational structure, arises without substantial concerns regarding the climatically rational design, the appropriate orientation of the building elements and the arrangement of the openings in relation to the prevailing winds, therefore eliminating the positive impact of bioclimatic architecture. Linear building structures appear in all directions, with some of them being particularly unfavorable in terms of solar gains, sun protection, ventilation and adequate lighting.

The integration of bioclimatic design and environmentally-concerned architecture principles in the design of school buildings in addition to comfort conditions, can help to reduce energy consumption for heating, cooling and lighting as well as increase user comfort and productivity.

With regard to the surrounding area of the school building, the regulatory role of the outdoor area to improve comfort conditions is not sufficiently utilized. The improvement of the microclimatic data of the immediate environment is not sought through the appropriate planting and the selection of the appropriate coating materials. In all typical schools, planting is treated haphazardly rather than as a requirement for sustainable outdoor design.

## 10.8. Chapter Summary

The Technical Services of the Ministry of Education, Culture, Sports and Youth have the responsibility for ensuring the necessary building infrastructure for the operation of public education. During the school year 2018-2019, a total of 275 kindergartens, 327 primary schools and 124 high schools operated. The majority of school buildings in Cyprus are a product of the design of the Technical Services of the Ministry of Education and Culture from the time of its establishment in the

Ottoman period . A significant number of school buildings were erected in the years following the Turkish invasion of 1974, to meet the building needs that arose, as previously mentioned. These were two-storey buildings, characterized by strong standardization in their design and construction implementation. These school buildings represent the majority of school buildings in Cyprus and were constructed without meeting pre-defined energy efficiency requirements.

For the need of the present thesis, a secondary school in the urban area of Nicosia, Cyprus was selected as a representative case study for in-depth investigation. The Archbishop Makarios III Secondary School was chosen as the case study. The school building incudes all the common characteristics of the typical school building and falls in a climatic zone where the adaptation measures can be applied in the majority of climatic zones in Cyprus. Additionally, the selected building has linear classrooms in different orientations therefore allowing the evaluation of thermal and energy performance in smaller study models. Finally, the selection of a school building of secondary education allows the evaluation of performance through questionnaires as students are more mature compared to primary school and are able to understand the questions and follow common curriculum.

# Chapter 11. Methodology to assess thermal comfort and energy performance of existing and upgraded educational buildings under current and future climatic scenarios

## 11.1. Introduction

This chapter presents the methods employed to assess thermal comfort and energy performance of educational buildings under current and future climatic scenarios under existing state and proposed adaptation measures. In this study, the experimental approach was performed in naturally-ventilated secondary school classrooms in Nicosia, Cyprus. Fieldwork procedures during cool, intermediate and warm conditions of the local school year combined with the measurement of physical variables of the classrooms with a survey of students' subjective responses, using questionnaires specifically designed for the target age group. Additionally, a calibrated model through software simulation was used to assess the performance of educational buildings under the future climatic scenarios. Additionally, feasible techniques that can be applied in educational buildings in Cyprus are described to improve thermal and energy performance of educational buildings, among which may be a thorough examination of thermal properties and construction detailing of buildings, the geometry of solar shading systems, operational concerns as well as mild technical system as heat recovery ventilation. This chapter first presents the environmental monitoring equipment and the measurement procedure of the physical environment and describes the experimental procedure undertaken for the investigation of the effectiveness of natural ventilation. Secondly, the methods used for the administration of the comfort survey and the design of the thermal comfort questionnaire are described. Thirdly, this chapter presents the methodology for the analysis through software simulation giving detailed information about the software used, modelling and validation, climatic scenarios, as well as adaptation measures for improved thermal and energy performance and minimization of overheating. Finally, retrofitting measures for the calculation of their cost-effectiveness are presented. Each subsection is associated with the relevant data analysis methodology.

## 11.2. Quantitative study through field measurements

### *11.2.1. Environmental data collection procedure, time of field survey and instrumentation*

In order to conduct schools-based research, permission from the Ministry of Education and Culture, Secondary General Education was obtained (Appendix A); whilst authorisation to conduct the case study research in the Archbishop Makarios III Secondary School, was granted by the School District office of Aglantzia (Appendix B).

The **first series of measurements** was carried out from December 2017 to August 2018 in order to cover all seasons, in classrooms with different orientation, roof exposure and structure difference. The intention was to use this data to understand the thermal performance of educational buildings with classrooms in different orientations through air temperature and relative humidity that will give feedback on at what periods and selected classrooms the thorough investigation will take place. Figure 11.1 is a diagrammatic plan of the selected classrooms that were monitored for the whole period of the field survey and Table 11.1 records the types of classrooms, their orientation and the data logger names that were installed in each one from December 2017 to August 2018 in order to cover all seasons. The characterization of the classrooms in terms of orientation is done according to the direction of the main openings.

Table 11.1. Location of data loggers.

| Classroom | Orientation | Data logger name (usb) |
|---|---|---|
| **Ground floor** | | |
| 3 – library | West | 24 |
| 10 – classroom | South | 47 |
| 18 – classroom of art | East | 49 |
| 27 – classroom of music | North | 36 |
| 29 – classroom | South | 37 |
| **First floor** | | |
| 35 – classroom | South | 19 |
| 36* – classroom | South | 20 |
| 37 – classroom | South | 21 |
| 38 – classroom | South | 22 |
| 42 – classroom of math | South | 44 |
| 48 – classroom | East | 35 |
| 49 – classroom | East | 34 |
| 51 – classroom | East | 33 |
| 52 – classroom | East | 32 |

***Classroom 36 has opposite orientation of windows compared to the windows of the building complex**

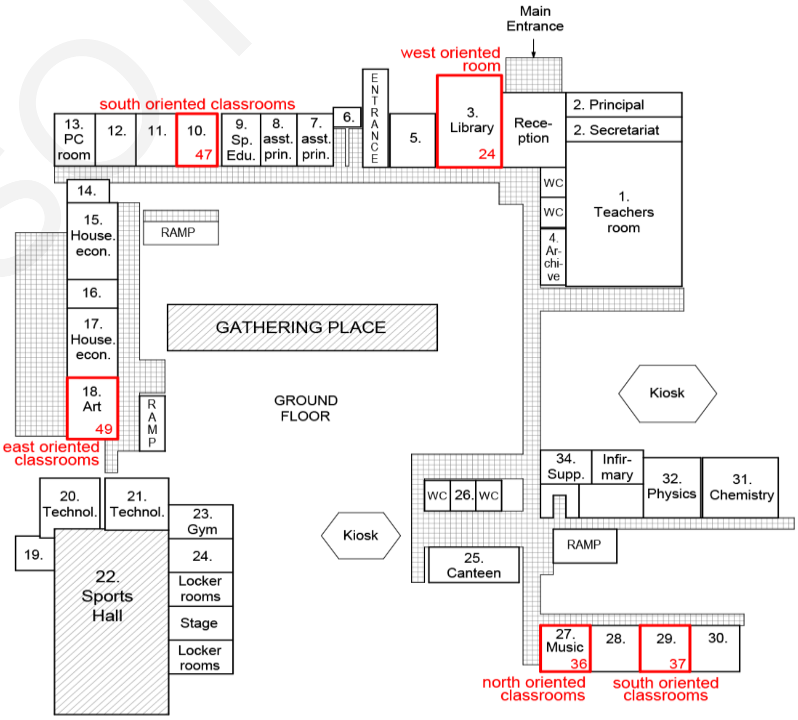



Figure 11.1. Diagrammatic plan of the ground floor of the Archbishop Makarios III Secondary school and with red lines are the selected classrooms with the indicated number of HOBO data logger.

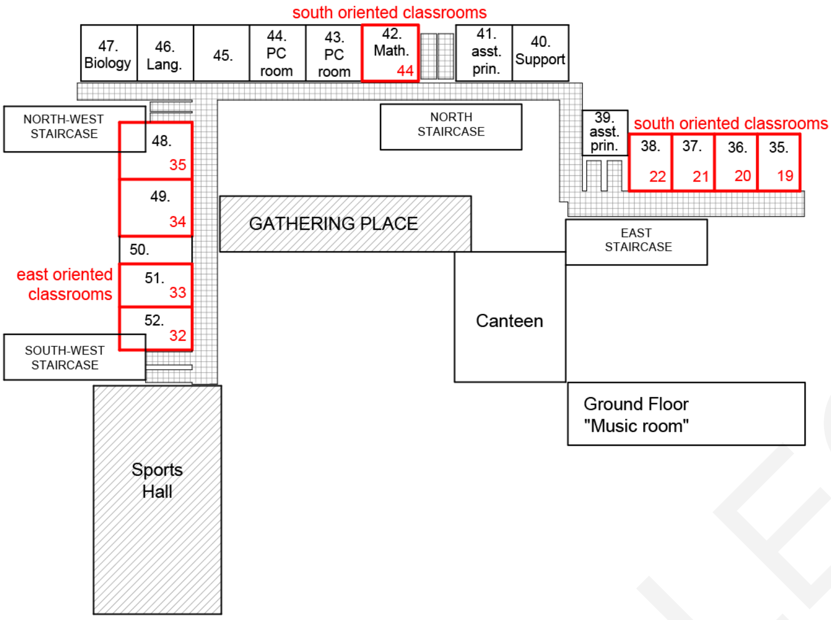



Figure 11.2. Diagrammatic plan of the first floor of the Archbishop Makarios III Secondary school and with red lines are the selected classrooms with the indicated number of HOBO data logger.

For the needs of the study, selected classrooms were analysed for each seasonal period. For the annual recording, the thermal behaviour of school buildings is analyzed for three periods as follows:

- 10th of February – 16th of February 2018 (winter)
- 31st of March- 06th of April 2018 (intermediate)
- 19th of May- 25th of May 2018 (summer)

Specifically, for each period comparison was made in:

(a) classrooms with different orientations and same roof exposure, i.e. (i) classroom with exposed roof to the outside environment: south (USB 21), east (USB 33), north (USB 36), west (USB 24), and (ii) classrooms in the ground floor covered by another classroom: south (USB 47) and east (USB 49);

(b) classrooms with same orientations and different roof exposure, i.e. comparison between south classroom in the first floor with its roof exposed to the external environment (USB 21) with south classroom in the ground floor covered by another classroom on the top (USB 47) and east classroom in the first floor with its roof exposed to the external environment (USB 33) with east classroom in the ground floor covered by another classroom (USB 49); and,

(c) classrooms with the same orientation but different structure in terms of sun protection. Specifically, comparison is made between the classroom in the south orientation of the first floor (USB 21) and the classroom located in the ground floor with its roof exposed to the external environment and a horizontal louver of 0.50m depth as a shading system of south openings instead of the corridor of 2.00 m located in typical classrooms.

The analysis was made during occupied period (07:30-13:35), for the whole day (00:00-24:00) and during the weekends where no technical system is provided. It is noted that some classrooms were also used in the afternoon (14:45-18:00) with a smaller number of occupants, i.e., 6-8 in each classroom.

The **second series of measurements** used equipment that was more specialized and focused on selected periods for in-depth investigation in the southern classrooms of the first floor (Figure 11.2: classrooms 35,36,37,38 and Figure 11.3) as the worst-case scenario, which received significant solar radiation and has the highest temperatures during the warm period compared to other orientations. The selected periods refer to winter (i.e. the 10th of February to the 16th of February 2018) when heating systems were switched on, to the intermediate period (i.e. the 5$^{th}$ of March to the 9$^{th}$ of March 2018) and to the warmest period of the school year before the final examination of June (i.e. the 19th of May to the 25$^{th}$ of May 2018). Data was recorded during weekdays and weekend in order to investigate the contribution of occupants and of technical systems. Additionally, during winter and summer, the objective was to evaluate the thermal comfort conditions of educational buildings under a range of diverse ventilation strategies and window opening configurations. Methodology and results of the experimental procedure are described in **Chapter 11.2.2** and **Chapter 15.2.**

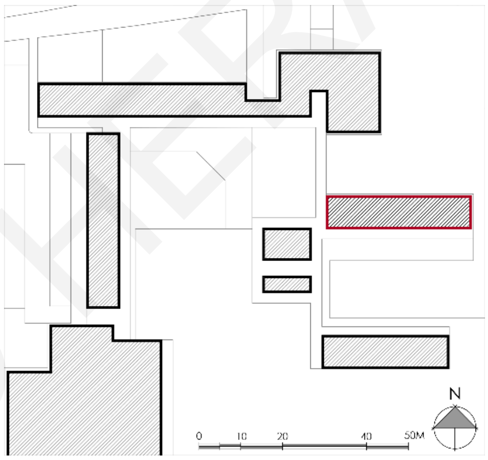



Figure 11.3. Master plan layout of a typical school premises in Cyprus. The building part that includes the selected classrooms under study is marked in red.

The pattern of occupancy for each classroom varied during the week and day (Table 11.2 and 11.3). It is noted that some classrooms were also used in the afternoon (14:45-18:00) with a smaller number of occupants, i.e., 6-8 in each classroom. Worth mentioning is also the fact that technical heating during winter is available through a central heating system with hot water radiators and diesel heated boilers between 07:00-10:00 every weekday and 14:45-17:45 on Monday, Tuesday, Thursday and Friday. Moreover, some classrooms due to its use have additional air conditioning handled by the teacher.

Table 11.2. School Timetable

| | Schedule 1 | Schedule 2 | |
|---|---|---|---|
| **Period** | **Monday, Tuesday, Thursday** | **Wednesday, Friday** | **Technical Heating** |
| **1** | 07:30 – 08:10 | 07.30 – 08.15 | ■ |
| **2** | 08:10 – 08:50 | 08.15 – 09.00 | ■ |
| **1st break** | 08:50 – 09:10 | 09.00 – 09.20 | ■ |
| **3** | 09:10 – 09:50 | 09.20 – 10.05 | ■ |
| **4** | 09:50 – 10:30 | 10.05 – 10.50 | – |
| **2nd break** | 10:30 – 10:50 | 10.50 – 11.10 | – |
| **5** | 10:50 – 11:30 | 11.10 – 11.55 | – |
| **6** | 11:30 – 12:10 | 11.55 – 12.40 | – |
| **3rd break** | 12:10 – 12:15 | 12.40 – 12.50 | – |
| **7** | 12:15 – 12:55 | 12.50 – 13.35 | – |
| **8** | 12:55 – 13:35 | – | – |
| **Afternoon session** | 14:45–18:00 | 14:45 – 18:00 | ■ (except Wednesday) |

Table 11.3. Occupancy pattern in each classroom under study, i.e., R1 (classroom 38), R2 (classroom 37), R3 (classroom 37) and R4 (classroom 36) in the periods (a) 12th of February to the 16th of February 2018 and (b) the 5th of March to the 9th of March 2018 and (c) the 19th of May to the 25th of May 2018. Dots indicate occupied classrooms during specific time-periods of the day.

| (a) | MONDAY | | | | | | | | TUESDAY | | | | | | | | WEDNESDAY | | | | | | | THURSDAY | | | | | | | | FRIDAY | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| R1 | | ■ | ■ | | | | ■ | | | ■ | ■ | | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | | | ■ | ■ | | | ■ | | ■ | | ■ | ■ | ■ | | | | | ■ |
| R2 | | | ■ | ■ | | | | ■ | ■ | ■ | | | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | | | | ■ | ■ | | ■ | ■ |
| R3 | | ■ | | ■ | | | ■ | | | | | ■ | | | | | | ■ | ■ | | ■ | | | ■ | | | ■ | ■ | | ■ | | | | ■ | | | ■ | ■ |
| R4 | ■ | | | ■ | | | | ■ | | | ■ | | ■ | | ■ | ■ | | | ■ | ■ | | ■ | | | ■ | | | ■ | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

| (b) | MONDAY | | | | | | | | TUESDAY | | | | | | | | WEDNESDAY | | | | | | | THURSDAY | | | | | | | | FRIDAY | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| R1 | | ■ | ■ | ■ | | | ■ | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | | | ■ | | ■ | | ■ | ■ | ■ | ■ | | | | ■ |
| R2 | | | ■ | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | | | | ■ | ■ | | ■ | ■ |
| R3 | | ■ | | | | | ■ | | | | | | | ■ | ■ | | | ■ | | | ■ | | | ■ | | | ■ | ■ | | ■ | | | | ■ | ■ | | ■ | ■ |
| R4 | ■ | | | ■ | | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | | ■ | ■ | ■ | | ■ | ■ | | ■ | | | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |

| (c) | MONDAY | | | | | | | | TUESDAY | | | | | | | | WEDNESDAY | | | | | | | THURSDAY | | | | | | | | FRIDAY | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| period | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| R1 | | ■ | ■ | ■ | | | ■ | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | | ■ | ■ | | | ■ | | ■ | | ■ | ■ | ■ | ■ | | | | ■ |
| R2 | | | ■ | | | | | ■ | ■ | ■ | | | | | | ■ | ■ | ■ | ■ | | | ■ | ■ | ■ | ■ | ■ | | ■ | ■ | | | | | ■ | ■ | | ■ | ■ |
| R3 | | ■ | | | | | ■ | | | | | | | ■ | ■ | | | ■ | | | ■ | | | ■ | | | ■ | ■ | | ■ | | | | ■ | ■ | | ■ | ■ |
| R4 | ■ | | | ■ | | ■ | ■ | ■ | ■ | | ■ | ■ | ■ | | ■ | ■ | ■ | | ■ | ■ | | ■ | | | ■ | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | |

Indoor environmental variables required for the assessment of thermal comfort were collected in parallel to questionnaire surveys in the selected classrooms. The following criteria were considered to develop an indoor measurement protocol:

• Instrument specification, resolution and accuracy

• Position of the instrument

• Students' visual access and routine activity

• Time of the measurement

• Data retrieval

*11.2.1.1. Instrument specification and accuracy*

Instrumentation consisted of HOBO data loggers, which was placed to measure air temperature and relative humidity continuously in classrooms with different orientation (east, north, and south) and floors from December 2017 to August 2018. The data logging interval of the equipment was 5 minutes. The units operated with rechargeable batteries and their screen display was set to off. Four LSI-Lastem Heat Shield base modules (ELR610M) were employed to measure air temperature, globe temperature, air velocity and relative humidity in four typical classrooms used for general educational purposes, on the first floor of the building under study, with south orientation for in-depth investigation. Based on these variables the operative temperature can be calculated. In order to measure air velocity, a Hot wire omnidirectional LSI Anemometer ESV125 was connected to the Lastem to produce measurements. The data logging interval of the was 10s. The data during the cold winter period was selected from the 10$^{th}$ of February to the 16$^{th}$ of February 2018, as this represents the coldest period of the year, followed by a more detailed investigation few days later, between the 3$^{rd}$ and 9$^{th}$ of March 2018. Finally, the data of the warmest period was recorded from the 19$^{th}$ of May to the 25$^{th}$ of May 2018 respectively, as this period represents the hottest period of the school year. The units operated with electric supply for long periods. Additionally, the Extech CO210 data logger was used in selected classrooms over the selected periods in order to investigate the air quality of the classrooms (please see more details in **Chapter 12 and Chapter 16**). The equipment obtained data over a logging interval of 5 minutes and operated with electric supply. Moreover, HOBO and Extech CO210 were used to verify the LSI-Lastem Heat Shield base module and identify any significant variation between them. At the same time, an outdoor weather station was installed on the building's roof, at a height of 10m above street level, i.e. 4 metres above the regular height of buildings found in the immediate vicinity. The outdoor conditions including temperature, humidity, wind speed, solar radiation and precipitation were recorded for the whole duration of the study. The specifications of the measurement instruments are summarised in Table 11.4.

Table 11.4. Instrument specifications.

| Name | Parameter | Range | Accuracy |
|---|---|---|---|
| **LSI-Lastem Heat Shield base modules (ELR610M)** | Natural Wet Bulb Temperature | -20 – 60 °C | ±0.3 °C |
| | Globe Temperature | -20 – 60 °C | ±0.3 °C |
| | Dry Bulb Temperature | -20 – 60 °C | ±0.8 °C |
| | | | ±0.4 °C (10-40 °C) |

| | | | |
|---|---|---|---|
| | Relative Humidity | 0 – 100 % | 1.8% RH (10-90%) |
| **Hot wire LSI Anemometer ESV125** | Air Speed | 0.01 – 20 m/s | ± 10 cm/s (0.5-1.5 m/s) 4% (>1.5 m/s) |
| **UX100-003 HOBO data logger** | Air Temperature | -20° to 70°C | ±0.21°C (0° to 50°C) |
| | Relative Humidity | 15% to 95% | ±3.5% (25% to 85%) |
| **Extech CO210 data logger** | Air Temperature | -10 to 60°C | Not available |
| | Relative Humidity | 0.1 to 99.9% | Not available |
| | $CO_2$ concentration | 0 to 9,999ppm | Not available |
| **Vantage Pro 2 Plus weather station** | Air Temperature | -40 – 65 °C | ±0.3 °C |
| | Relative Humidity | 1 – 100 % | ±3 % |

*11.2.1.2. Position of the equipment in the classroom*

The sensors were placed at a height of 1.1 m above floor level, which fairly corresponds to the mean height of window openings, i.e., B-H and the height level of the head of sitting students as defined by the EN 7726:2001 [446].

The HOBO data loggers that recorded the temperature and humidity continuously from December 2017 to August 2018 in classrooms with different orientation, were placed as shown in Figures 11.1 and 11.2. The devices could not be placed in the middle of the room that would be the ideal, as they would obstruct the normal class schedule. In addition, they were located away from heating systems to avoid any interference in the readings. Care was also taken to minimize the risk of instruments being accidentally bumped into by classroom users.

The equipment for the selected periods in the south facing classrooms was placed in selected locations, as shown in Figure 11.4.

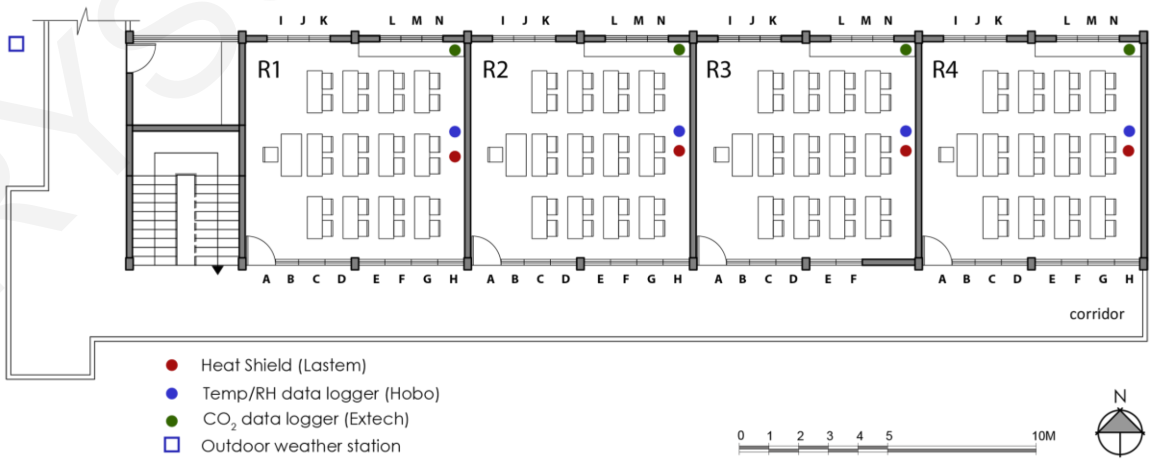



Figure 11.4. Plan layout of a typical classroom of secondary schools in Cyprus where the openings A to N, and the locations of the installed recording equipment, for indoor and outdoor environmental conditions are indicated.

Figure 11.5. Location of equipment in the classroom.

Figure 11.6. Outdoor weather station installed on the building's roof, at a height of 10m above street level, i.e. 4 metres above the regular height of buildings.

*11.2.1.3. Data retrieval*

For the continuous measurements, the data were transferred and downloaded to the computer and time stamped accordingly, for the corresponding class number every two months. For the in–depth investigation of the south-oriented classrooms, at the end of each survey period all measured physical parameters were transferred and downloaded to the computer and time stamped accordingly for the corresponding class number. After each survey period, the instruments were turned off. The anemometers were retracted, and the sensing element of each air speed probe was located inside the handle to be protected and for safety purposes.

*11.2.2. Proposed experimental scenarios for educational buildings upgrade using proper operation of windows*

The positive contribution of natural ventilation through proper operation of windows is well established as an easy passive strategy that can be applied if external conditions allow for it [86]. The open structure of the typical school building and especially the layout of the classrooms in the form of a linear disposition, allows the existence of openings along the two side of the classrooms in the majority of the classrooms, ensuring cross ventilation of the functional space.

Utilizing natural ventilation to cool school buildings requires a sufficient temperature difference between indoor and outdoor temperatures. The use of winds during the summer season to improve the conditions of thermal comfort is indicated during the evening and early morning hours of the day, when temperatures are at relatively low levels. A positive contribution to the improvement of thermal comfort through natural ventilation can be achieved at higher temperature levels since there is an increased speed of air movement. The use of prevailing winds to cool the functional areas of the building can be optimized by providing cross ventilation. Cross ventilation is achieved by simultaneously opening windows and clerestories on both sides of the classroom.

Night ventilation ensures thermal discharge and cooling of the building envelope, thus reducing the cooling needs for the next day. This effect is enhanced by the thermally exposed mass of the building (reinforced concrete roofs and perforated ceramic brick walls), so that it is possible to store "cold" during the night.

A field study was carried out to assess the effect of different ventilation strategies and window opening configurations on thermal comfort in educational buildings during the winter and summer period, i.e. from the 10$^{th}$ of February to 13$^{th}$ of February, 2018, and from the 19$^{th}$ of May to 25$^{th}$ of May 2018 respectively in four south-oriented classrooms of the the Archbishop Makarios III Secondary School. Data were collected when classrooms were fully occupied as well as when no one was present. The methodology for the environmental data collection and instrumentation is described in **Chapter 11.2.1.**

The occupancy of a classroom differed during the week. Some classrooms were used for auxiliary activities in the afternoon (14:45-18:00), but noticeably with a lower occupancy rate, i.e. 6-8 in each classroom. In terms of technical systems, it is noted that a central heating system was in operation between 07:00-10:00 every weekday and between 14:45-17:45 on Monday, Tuesday, Thursday and Friday during the winter period.

The various ventilation strategies and window opening configurations which were studied during the warmer summer months and cold winter period are presented in Table 11.5.

The first experimental procedure was carried out during the summer period. The objective was to indicate the most effective cooling strategy, thus, both single-sided and cross-ventilation strategies were employed for different times of the day in the four south facing classrooms. Specifically, the different ventilation strategies were examined for four consecutive days, i.e. during the weekend, and on Monday and Tuesday. In Case 1, single-sided daytime ventilation occurred in the morning hours, i.e. 07:00-13:30 with openings A, C, and F remaining fully open. For comparison reasons, in Case 4, cross-ventilation also occurs in the morning hours, i.e. 07:00-13:30 with openings A, C, F, J and

M remaining fully open. In Case 2, cross-ventilation was proposed for both daytime and nigh-time, i.e. 07:00-13:30 and 21:00-07:00 with openings A, C, F, J and M remaining fully open. In Case 3, the classroom remained closed during the teaching hours to reduce heat gains; however, the door (i.e. opening A) remained open throughout the day to maintain indoor air quality and cross-ventilation is proposed during the night, i.e. 21:00-07:00, to reduce the extensive heat stored in the building envelope. It is noted that in all cases under study that employed night ventilation, the door of the classroom remained closed for safety reasons.

The second experimental procedure was carried out during the winter period. The objective was to assess the thermal comfort conditions as well as indoor air quality of educational buildings, using different window opening patterns. Thus, window opening patterns of single-sided ventilation strategies were examined in four south facing classrooms. The data was monitored for both occupied and unoccupied hours. Specifically, the different experimental ventilation strategies were examined for 4 consecutive days i.e. during the weekend, on Monday and Tuesday. The openings that remained opened were C and F. In Case 4, windows were opened during all break times (08:50-09:10, 10:30-10:50 and 12:10-12:15), in Case 3, windows were opened during the last two breaks, while in Case 2, windows were only opened during the last break at midday. In Case 1, i.e. reference scenario, all the openings remained closed.

Table 11.5. Ventilation strategies and window opening patterns examined during the field summer and winter period. Dots indicate open windows during the specific time of the day.

| Case | Ventilation strategies | Window opening patterns | | | |
|---|---|---|---|---|---|
| | | Openings remained open | | Operation | |
| **SUMMER PERIOD** | | | | | |
| | | Window name | Total Size ($m^2$) | Day (07:00-13:35) | Night (21:00-07:00) |
| **Case 1 (R1)** | Single-sided | A, C, F | 3.65 | ■ | - |
| **Case 2 (R2)** | Cross | A, C, F, J, M | 4.75 | ■ | ■ |
| **Case 3 (R3)** | Cross | A, C, F, J, M | 4.75 | - | ■ |
| **Case 4 (R4)** | Cross | A, C, F, J, M | 4.75 | ■ | - |

| **WINTER PERIOD** | | | | | | |
|---|---|---|---|---|---|---|
| | | Window name | Total Size ($m^2$) | 1st break 20 mins | 2nd break 20 mins | 3rd break 5 mins |
| **Case 1 (R1)** | No ventilation | - | | - | - | - |
| **Case 2 (R2)** | Single Sided 1 | C, F | 1.75 | - | - | ■ |
| **Case 3 (R3)** | Single Sided 1 | C, F | 1.75 | - | ■ | ■ |
| **Case 4 (R4)** | Single Sided 1 | C, F | 1.75 | ■ | ■ | ■ |

*R1, R2, R3 and R4 represent the classroom where each strategy was applied*

### *11.2.3. Data analysis methodology*

#### *11.2.3.1. Preliminary analysis of air temperature and relative humidity*

Objective data were collected from the equipment and entered into Microsoft Excel, which enable data storage. Data were classified based on the season of the field study. The indoor conditions were assessed based on the recorded environmental data. For each classroom the maximum, minimum, average, standard deviation and fluctuation was shown.

#### *11.2.3.2. Thorough research using operative temperature*

Objective data were collected from the equipment and entered into Microsoft Excel, which enabled data storage. The operative temperature and the mean radiant temperature were calculated for each classroom and imported into Microsoft Excel together with other measured physical variables. Data was classified based on the season of the field study. The indoor conditions were assessed based on the recorded environmental data. Several indices and mathematical models were used to analyse the indoor comfort conditions. This methodology was followed for the assessment of the educational building in existing state as well as for the proposed experimental scenarios for proper ventilation.

##### *11.2.3.2.1. Adaptive comfort models*

Thermal comfort was assessed using the Adaptive Comfort Standards (ASC) which is incorporated in the EN 15251:2007 [87] (old version of EN 16798-1:2019 [118]). The Adaptive Comfort Standard (ASC) is solely employed in buildings that use natural ventilation whose occupants have different expectations to residents of artificially supported buildings, because of their ability to adapt to outdoor conditions [113]. The occupants engaged in non-active activities with a metabolic rate fluctuating between 1.0 to 1.3 met while clothing insulation is anticipated to 1 clo for winter and 0.5 clo for summer. It should be noted that only during the heating period, a technical system operates for limited time of the day; therefore, the building is considered as free-running building. Observing the information of free-running buildings alone, the relationship between the indoor thermal comfort temperature and the outdoor running mean temperature can be calculated by:

$$T_c = 0.33T_{rm} + 18.8 \qquad \text{(Eq. 11.1)}$$

where, $T_c$ is the predicted comfort temperature when the running mean of the outdoor temperature is $T_{rm}$. The prevailing mean outdoor air temperature ($T_{rm}$) is the arithmetic average of the mean daily outdoor temperatures over a period of seven consecutive days prior to the day in question.

The CIBSE recommendation is that newly constructed buildings, extensive restorations and alterations should abide by Category II in EN15251:2007. Category II forms 80% of the acceptability limits of indoor operative temperatures which are calculated using Equations (11.2) and (11.3), while, the corresponding 90% of acceptability limits are reached when subtracting 1°C from the upper 80% acceptability limit and adding 1°C to the lower 80% acceptability limit [87].

Lower 80% acceptability limit: $T_c = 0.33\ T_{rm} + 15.8$ (Eq. 11.2)

Upper 80% acceptability limit: $T_c = 0.33\ T_{rm} + 21.8$ (Eq.11.3)

It is worth mentioning that according to EN 16798-1:2019, which is a revision of EN 15251:2007, the lower acceptability limit for buildings in Category II is extended by 1°C compared to the current standard, indicating that people tend to be more adaptive to lower temperatures. However, the analysis of the present study is based on the EN 15251:2007, which was currently in force during the monitoring period.

For the purposes of this study, the calculation of the operative temperature ($t_o$) is based on an average air temperature ($t_a$) and mean-radiant temperature ($t_r$), as shown in Equation (11.4). Value $A$ is a function of the relative air speed ($V_r$). When $V_r$ is below 0.2m/s, A is defined at 0.5, when $V_r$ is between 0.2m/s and 0.6 m/s, A is 0.6 and when $V_r$ is between 0.6 m/s and 1 m/s, A is defined at 0.7.

$$\mathrm{t_o} = \mathrm{A\ t_a} + (1 - \mathrm{A})\mathrm{t_r} \quad \text{(Eq.11.4)}$$

Moreover, air temperature ($t_a$) is recorded directly, while mean radiant temperature ($t_r$) is calculated using Equation (11.5). The parameters included in Equation (11.5) are globe temperature ($t_g$), air velocity ($V_a$), air temperature ($t_a$), globe diameter ($D$) and emissivity ($\varepsilon$).

$$t_r = \left[(t_g + 273)^4 + \frac{1.10\ x10^8 V_a^{0.6}}{\varepsilon\ D^{0.4}}(t_g - t_a)\right]^{\frac{1}{4}} - 273 \quad \text{(Eq.11.5)}$$

*11.2.3.2.2. Temperature Difference Ratio*

For the evaluation of the effectiveness of passive cooling strategies with different ventilation configurations, the Temperature Difference Ratio (TDR) proposed by La Roche and Givoni [68] was used. The TDR is estimated for each day based on Equation (11.6), as the ratio of the difference between the maximum outdoor air temperature ($T_{max\_out}$) and the maximum indoor temperature ($T_{max\_in}$), to the fluctuation of the outdoor temperature ($T_{fluctuation\_out}$), i.e. the difference between the maximum outdoor air temperature ($T_{max\_out}$) and the minimum outdoor air temperature ($T_{min\_out}$).

$$\mathrm{TDR} = \frac{T_{max\_out} - T_{max\_in}}{T_{fluctuation\_out}} \quad \text{(Eq. 11.6)}$$

It should be noted that this Equation (11.6) can be used when the correlation between the reduction of the maximum air temperature ($T_{max\_out} - T_{max\_in}$) and the outdoor temperature fluctuation ($T_{fluctuation\_out}$) is great. A higher value of TDR indicates a larger temperature difference between indoors and outdoors, and thus a more effective cooling strategy. The highest possible value of TDR is one, and this can also be expressed as a percentage.

*11.2.3.2.3 Heating and Cooling Degree-Hours*

With regards to the thermal environment, the degree-hours which fall outside of both the higher and lower limit margins can be employed as a performance indicator for building for either the warm or cold seasons. The heating/cooling degree-hours (HDH and CDH) are defined as the sum of the difference between hourly average temperatures and the lower/upper acceptability limit of indoor operative temperature as defined in EN 15251:2007. The value of the heating degree-hours (HDH) in any given day is defined using the Equation (11.7).

$$HDH = \sum_{i=1}^{N}\left(T_{lower\_limit} - To_{average}\right)^{+} \quad \text{(eq. 11.7)}$$

In the Equation (11.7), N is the number of hours in a day with average hourly operative temperature lower than the lower acceptability limit, $T_{o\_average}$ is the average hourly operative temperature, and $T_{lower\_limit}$ is the lower acceptability limit to which the degree-hours are calculated. The "+" superscript indicates that only positive values of the bracketed quantity are taken into account in the sum.

Similarly, the cooling degree-hours (CDH) in any given day is defined using the Equation (11.8), where $T_{upper\_limit}$ is the upper acceptability limit to which the degree-hours are calculated:

$$CDH = \sum_{i=1}^{N}\left(To_{average} - T_{upper\_limit}\right)^{+} \quad \text{(Eq. 11.8)}$$

## 11.3. Qualitative survey through questionnaires

### *11.3.1. Procedure for conducting field research*

The study considered thermal comfort and indoor air quality qualitative survey through gathered data from questionnaires to be used in the assessment of comfort conditions. The investigation aimed to record the opinion of the users of the school environment, regarding the conditions of total comfort of the school buildings. This approach sought to capture the subjective point of view of participants, introducing parameters relating to the biological, emotional and psychological experience of students.

The results of this part of the research, although subjective, are a useful tool of the research process, feeding the objective recording, analysis and simulation of the conditions of total comfort. The multi-criteria recording and evaluation of comfort conditions ensures the most complete, in terms of comfort, approach to the built environment.

The questionnaire was submitted for approval and licensing to the Directorate of Secondary Education of the Ministry of Education, Culture, Sport and Youth of the Republic of Cyprus (Appendix A). Additionally authorisation to conduct research in Archbishop Makarios III Secondary School granted by the School District office of Aglantzia (Appendix B). The Centre for Educational Research and Evaluation (KKEA), which examined the request for research, provided relevant comments and recommendations regarding questionnaire and finally approved it (Appendix C).

In addition to informing the principals, teachers and students involved about the content of the research, relevant assurances were given in advance for the appropriate and confidential handling of the research data. The parents and guardians of the students were informed about the purpose of the research and the process of conducting it, through a letter prepared by the author and a parent consent form was given allowing for their children to complete the questionnaire and was signed from the majority of parents (90%) before the dissemination of questionnaires (Appendix D). The process of issuing, collecting and evaluating the questionnaire, fully ensured the anonymity of students. The participation of students in the research was optional.

The research was conducted in consultation with the principal and teachers of the selected school. The questionnaire was administered during teaching periods indicated by the school management, with the most possible minimization of the effects on the teaching work of the schools. The time to complete the questionnaire, including the time of administration, explanation and compilation of the questionnaire, was about 15 – 20 minutes.

### *11.3.2. Structure and design of a research tool*

The purpose of the questionnaire is to investigate the environmental comfort conditions in a typical secondary school buildings. In its final form, as formulated after the correction of the Educational Research and Evaluation Centre (i.e. KEEA, see Appendix E: Sample of field research questionnaires of this thesis), it consisted of five sections with a total of 26 questions.

Questionnaires were specifically designed for the target age group based on developmental psychology [447]. Additionally, the questionnaire was developed based on the study performed by de Dear and Brager [134] and Humphreys and Nicol [105].

Questionnaires were filled in by 317 secondary school students during the school year 2017-2018. The survey was conducted during the winter period, from the 15th of January to the 17th of January 2018, and by 289 students during the summer period, from 09th of May to 11th of May 2018. Students' age ranged from 12 to 15 years old. Out of the total number of participants, 50% were boys and the other 50% were girls. The questionnaires were filled in by students while sitting in their classrooms during the teaching periods. The questionnaires included a series of questions divided into six main sections:

The **first section** includes questions related to:

- General information (date and time of completion of the questionnaire); and
- General elements of a school classroom (classroom orientation, position of the respondent's desk in the classroom).

The questions of the first section ensure the collection of data related to users and the school building under study. This data is necessary to evaluate and comment on the individual views of users.

The **second section** included questions related to:

- Gender, age;
- Clothing insulation; and
- Smoking.

The questions in the second section ensured the collection of data related to respondent's personal information which was necessary to evaluate while taking into account the individual views of users.

The **third section** dealt with thermal comfort conditions and includes questions concerning:

- Thermal sensation (TS);
- Thermal preference (TP);
- Thermal acceptability (TA);
- Air movement preference (AM); and
- Activity carried out in the last half hour.

The questions in the third section were intended to gather users' views on thermal comfort conditions. The aim is the comparative presentation of these data, with the quantitative (objective) data of recording and analysis and the drawing of relevant conclusions.

The **fourth section** dealt with air quality and humidity and includes questions concerning perception and preference of air as to:

- Dryness;
- Freshness;
- Odour;
- Movement; and
- Overall satisfaction.

The questions in the fourth section were intended to gather users' views on air quality conditions. The aim is the comparative evaluation of qualitative data with the quantitative (objective) data of recording and analysis and the drawing of relevant conclusions.

The **fifth** section dealt with lighting performance and includes questions concerning perception of natural lighting as to:

- Brightness/darkness;
- Uniformity;
- Glare issues; and
- Overall satisfaction.

The questions in the fifth section were intended to gather users' views on visual comfort conditions. The aim is the comparative presentation of these data, with the quantitative (objective) data of recording and analysis and the drawing of relevant conclusions.

The **sixth section** was about the possibilities offered to control comfort parameters of the classroom and includes questions regarding:

- Window operation;

- Curtain operation;
- Technical lighting system operation; and
- Wall fan.

The questions in the sixth section were intended to gather information about user behaviour in order to understand the engagement of users with the building. This set of data, although difficult to quantify, demonstrates the prevailing views of users. This behaviour was inserted in the simulation software.

**Finally**, there is a general question for general comfort within classroom with special reference to specific elements from any category of the parameters that the students do not like in the classrooms including cleanliness, insufficient lighting, noise, poor aesthetics of the space, unpleasant odours and others.

For this analysis of thermal comfort in a representative classroom in a typical educational building in Cyprus, seven-point and five-point Likert scale questions were included in the questionnaire. Table 10.6 summaries the scale of questionnaire for the thermal comfort survey.

For this analysis of thermal comfort in a representative classroom in a typical educational building in Cyprus, seven-point and five-point Likert scale questions were included in the questionnaire. Table 11.6 summarises the scale of questionnaires for the thermal comfort survey.

Table 11.6. Scales of questionnaires for the thermal comfort survey.

| **Parameter** | **Scale** | | | | | | |
|---|---|---|---|---|---|---|---|
| **Thermal sensation (TS)** | -3 | -2 | -1 | **0** | 1 | 2 | 3 |
| | cold | cool | slightly cool | **neutral** | slightly warm | warm | hot |
| **Thermal preference (TP)** | | -2 | -1 | **0** | 1 | 2 | |
| | | Much coole r | Cooler | **No change** | Warmer | Much warmer | |
| **Thermal acceptability (TA)** | | **1** | | | | 2 | |
| | | **Yes** | | | | No | |
| **Air movement preference (AM)** | | -2 | -1 | **0** | 1 | 2 | |
| | | Much less | A bit less | **No change** | A bit more | Much more | |

*Note: The ideal condition is indicated by bold*

### *11.3.3. Data analysis methodology*

Data from students' subjective responses to the questionnaire were coded and imported to a spreadsheet. The data were treated and analysed using statistical analysis methods in thermal comfort studies. The analyses were performed using Microsoft Excel and MATLAB. The characterization of thermal indices is associated with the descriptions of the mean, standard deviation and range in the form of percentage. Correlation analysis and significance *p*-value test were carried out to describe the degree of relationship between subjective and objective variables.

## 11.4. Dynamic software simulation

In order to assess the levels of thermal comfort and energy performance vulnerability of schools in Cyprus and the effectiveness of passive strategies both in the current and future climatic conditions, a dynamic software simulation was used.

### *11.4.1. Software*

There is a wide variety of software that can be used to perform calculations in order to analyse the energy use and thermal conditions of a building, such as Energy Plus, IES-VE, TRANSYS, ESP-r and TAS. Between the software recorded above, **IES-VE** (Integrated Environmental Solutions Limited Virtual Environment) is selected for this study because it includes an environment for the detailed assessment of building and system designs, allowing them to be optimized with regard to comfort criteria and energy use. Over the last 50 years, the IES-VE simulation tool has evolved into a robust and reliable simulation environment [448]. IES-VE has a sophisticated energy performance assessment capability compared to similar energy simulation tools [448]. Specifically, it can simulate over 40 measures of room performance, including air and radiant temperature, humidity, $CO_2$ concentration, sensible and latent loads, gains and ventilation rates, it can give comfort statistics, natural ventilation rates through individual windows, doors and louvres, surface temperatures for comfort analysis, plant performance variables, loads and energy consumption and carbon emissions [449]. Tables 11.7-11.12 illustrate the comparison of capabilities of different dynamic simulation programs (DSP) summarised in the above-mentioned issues.

Table 11.7. DSP natural ventilation capability [450].

| | Energy Plus | ESPr | IES-VE | TAS | TRANSYS |
|---|---|---|---|---|---|
| **Natural ventilation** | X | X | X | X | X |
| **Mixed mode** | X | | X | X | X |
| **Controllable openings based on internal or external conditions** | X | X | X | X | X |

Table 11.8. DSP indoor climatic conditions capability [450].

| | Energy Plus | ESPr | IES-VE | TAS | TRANSYS |
|---|---|---|---|---|---|
| **Indoor temperature** | X | X | X | X | X |
| **Floating temperature – no control** | X | X | X | X | X |
| **Temp based on loads sys feedback** | X | X | X | X | X |
| **Indoor relative humidity** | X | X | X | X | X |
| **Thermal comfort** | X | X | X | X | X |
| **Zone concentrations of $CO_2$** | | X | X | | X |

Table 11.9. DSP orientation and outdoor climate capability [450].

| | Energy Plus | ESPr | IES-VE | TAS | TRANSYS |
|---|---|---|---|---|---|
| **Orientation and Site Position** | X | X | X | X | X |
| **Outdoor Climate data** | X | X | X | X | X |

Table 11.10. DSP passive solar systems and solar protection capability [450].

| | Energy Plus | ESPr | IES-VE | TAS | TRANSYS |
|---|---|---|---|---|---|
| **User defined shading devices** | | | | | |
| **Shading device scheduling** | X | | X | X | X |
| **User specified shading control** | X | X | X | X | X |

Table 11.11. DSP natural lighting capability [450].

| | Energy Plus | ESPr | IES-VE | TAS | TRANSYS |
|---|---|---|---|---|---|
| **Interior illumination from windows etc.** | X | X | X | X | |
| **Stepped or dimming lighting controls** | X | | X | X | X |
| **Sky model** | | | | | |
| • **Isotropic** | | X | X | X | X |
| • **Anisotropic** | X | X | X | | X |
| • **User selectable** | | X | X | | X |
| **Daylight Illuminance Maps** | X | X | X | X | |

Table 11.12. DSP thermal and air tightness modelling capability [450].

| | Energy Plus | ESPr | IES-VE | TAS | TRANSYS |
|---|---|---|---|---|---|
| **Conduction Solution Method** | | | | | |
| • **Admittance method** | | | X | | |
| • **Transfer function** | X | | | X | X |
| • **Finite differene** | | X | X | | |
| **Internal heat capacity** | X | X | X | X | X |
| **Internal Convection coefficient** | | | | | |
| • **Temperature dependant** | X | X | X | X | X |
| • **Air flow dependant** | | X | X | X | |
| • **CFD based** | | | X | | |
| • **User defined** | | X | X | X | X |
| **Exterior convection coefficient** | | | | | |
| • **User defined** | X | X | X | X | X |
| • **Wind speed dependant** | X | X | X | X | X |
| **Shortwave radiation** | X | X | X | X | X |

| | | | | | |
|---|---|---|---|---|---|
| **Longwave radiation** | X | X | X | X | X |
| **Infiltration** | X | X | X | X | X |
| **Calculation of wind pressure coefficients** | | | X | X | |

### *11.4.2. Modeling and validation*

The IES-VE modelling of the selected educational building involved **two phases with four stages**:

**The first phase** considered the evaluation of educational buildings when supported by technical systems, while, **the second phase** considered the evaluation of educational buildings when are not supported by technical systems. Table 11.13 summarizes the simulation software phases and stages.

Table 11.13. Simulation software phases and stages

| **A. Current and Future climatic conditions – No technical systems** | **B. Current climatic conditions – Technical Systems** |
|---|---|
| **1. Existing State** | 3. Existing State |
| **2. Upgraded Building** | 4. Upgraded Building |

**First**, a model for the educational building was developed with a view to investigate and establish the thermal and energy consumption patterns of existing circumstances, both in the current and future climatic conditions without technical systems in order to examine the actual performance;

**Second**, a remodeled version of the educational building without technical systems was developed based on the suggested energy retrofitting solutions, to analyse the potential improvements of thermal and energy performance and acted as a preliminary analysis for the fourth stage.

**Third,** a model for the educational building was developed with a view to investigate the energy consumption in the building's existing state under the current climatic conditions, with the assumption that technical systems are provided to maintain indoor thermal comfort, in order to investigate the cost effectiveness of adaptation measures followed below.

**Fourth,** a remodeled version of stage three of the educational building with technical systems was developed in order to investigate the energy and cost-effectiveness of suggested energy retrofitting solutions.

The building was modelled in detail using IES and the model was validated using measured hourly indoor temperatures. Internal and external environmental data were registered as described in **Chapter 11.2.** To investigate the comfort and energy performance of typical school buildings, a classroom was selected in a two-story linear disposition. The studied classroom is located in the centre of the building, with rooms (heated areas) on both sides. Classrooms (heated area) also exists on the ground floor. The building elements exposed to the outdoor climatic conditions are the roof of the classroom and the two long sides, which include the openings (main and clerestories). The model is a faithful representation of the building and its operation profiles as accurately as possible. The building is set as operating in a free-running mode throughout the whole year in order to calculate the degree hours when the classroom exceeds the thermal comfort zone (Figure 11.7).

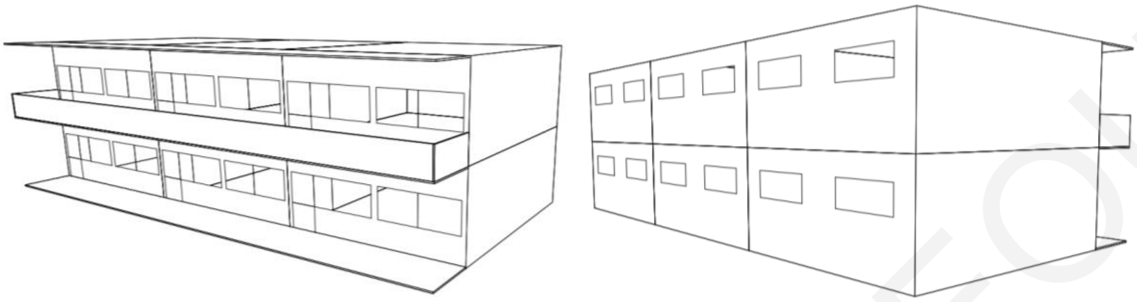


Figure 11.7. 3D sketch of the facades (main openings and clerestories) of a typical school building element in IES-VE.

IES combines several modules to perform dynamic whole-building energy analysis [399]. ModelIT is the single central 3D data model at the core of the IES that provides data shared by all modules. ApacheSim is a central simulation processor which enables assessment of building's thermal performance as well as the sharing of results and inputs across other IES modules, such as ApacheHVAC for modeling of HVAC systems, MacroFlo for airflow analysis, and SunCast for advanced 3D solar analysis. Moreover, VistaPro enables quick and easy analysis of the results from one or more simulations. Development of a detailed and realistic whole-building energy model required the use of all these modules. Therefore, Model-It, SunCast, Apache, MacroFlo, and VistaPro were used.

*11.4.2.1. Weather data*

Observed weather was recorded for the needs of this research from a weather station installed on the roof of the Archbishop Makarios III Secondary School. This gave, dry bulb temperature, wet bulb temperature, relative humidity, wind direction, wind speed and radiation. Other data were from the EPW for Athalassa (TMW) downloaded from Meteonorm v.7.1.11. Meteonorm is a meteorological database with climatologic data for solar engineering applications from every location on the globe For validation purposes, the data from the weather station were used; while, for the analysis of the performance of educational buildings the typical meteorological year (TMY) and the future climate of scenario A1B for 2050 and 2090 downloaded from Metenorm.

*11.4.2.2. Zoning approach and building geometry*

Internal and external dimensions and openings of the case study building were modelled carefully using to-scale drawings. The classrooms are divided into different thermal zones and were created using the ModelIt application within IES. Due to the internalised character of the educational buildings (having their large windows towards the yards) and their architectural design through linear arrangements which are distant from each other, the surrounding buildings are not as important, as they do not provide cast shadows and consequently not affect the thermal and energy behaviour of schools.

*11.4.2.3. Materials and construction*

In IES, the envelope construction refers to the assembly of multiple layers defined from outside to the inside where each layer represents a specific material defined, based on its physical properties (e.g., thickness, thermal conductivity, density, and specific heat). The thickness of each layer was taken from the final construction drawings provided by the Technical Services, whereas the thermophysical properties were taken from the "Thermal Insulation Guide" published by the local authority of the Energy Service, Ministry of Energy, Commerce and Industry.

The results of calculation of the thermal transmittance coefficients (W / m$^2$K) of the typical classroom in its current condition for external wall (Table 11.14), internal wall (Table 11.15), load-bearing structure (columns and beams) (Table 11.16), external roof (Table 11.17), internal floor (Table 11.18) and ground floor (Table 11.19) are presented below.

Table 11.14. Table of materials and characteristics of the external wall of the typical classroom in its current condition, for the calculation of the thermal transmittance coefficient of the external wall.

| **Materials External wall** | **Thickness d (m)** | **Thermal conductivity λ (W/mK)** | **Thermal Resistance R (m$^2$K/W)** | **Density ρ (kg/m$^3$)** | **Specific heat capacity Cp (KJ/KgK)** |
|---|---|---|---|---|---|
| Cement mortar | 0,025 | 1,00 | 0,025 | 1800 | 1.00 |
| Brickwork | 0,200 | 0,40 | 0,500 | 1000 | 1.00 |
| Cement mortar | 0,025 | 1,00 | 0,025 | 1800 | 1.00 |
| Internal surface thermal resistance **Rsi** | | | 0,130 | | |
| External surface thermal resistance **Rse** | | | 0,040 | | |
| **Thermal transmittance** | **U value** | **1,389** | **W/m$^2$ K** | **Thermal mass Cm (kJ/m$^2$K)** | **120** |

Table 11.15. Table of materials and characteristics of the internal wall of the typical classroom in its current condition, for the calculation of the thermal transmittance coefficient of the internal wall.

| **Materials Internal wall** | **Thickness d (m)** | **Thermal conductivity λ (W/mK)** | **Thermal Resistance R (m$^2$K/W)** | **Density ρ (kg/m$^3$)** | **Specific heat capacity Cp (KJ/KgK)** |
|---|---|---|---|---|---|
| Cement mortar | 0,025 | 1,00 | 0,025 | 1800 | 1.00 |
| Brickwork | 0,200 | 0,40 | 0,500 | 1000 | 1.00 |
| Cement mortar | 0,025 | 1,00 | 0,025 | 1800 | 1.00 |
| Internal surface thermal resistance **Rsi** | | | 0,130 | | |
| External surface thermal resistance **Rse** | | | 0,130 | | |
| Thermal transmittance | **U value** | **1,235** | **W/m$^2$ K** | **Thermal mass Cm (kJ/m$^2$K)** | **120** |

Table 11.16. Table of materials and characteristics of the load-bearing structure of the typical classroom in its current condition, for the calculation of the thermal transmittance coefficient of the load-bearing structure.

| **Materials Load-bearing structure (columns and beams)** | **Thickness d (m)** | **Thermal conductivity λ (W/mK)** | **Thermal Resistance R ($m^2K/W$)** | **Density ρ ($kg/m^3$)** | **Specific heat capacity Cp (KJ/KgK)** |
|---|---|---|---|---|---|
| Cement mortar | 0,025 | 1,00 | 0,025 | 1800 | 1.00 |
| Reinforced concrete with 2% steel | 0,300 | 2.50 | 0,120 | 2400 | 1.00 |
| Cement mortar | 0,025 | 1,00 | 0,025 | 1800 | 1.00 |
| Internal surface thermal resistance **Rsi** | | | 0,130 | | |
| External surface thermal resistance **Rse** | | | 0,040 | | |
| **Thermal transmittance** | **U value** | **2,941** | **$W/m^2$ K** | **Thermal mass Cm ($kJ/m^2K$)** | **225** |

Table 11.17. Table of materials and characteristics of the external roof of the typical classroom in its current condition, for the calculation of the thermal transmittance coefficient of the external roof.

| **Materials External roof** | **Thickness d (m)** | **Thermal conductivity λ (W/mK)** | **Thermal Resistance R ($m^2K/W$)** | **Density ρ ($kg/m^3$)** | **Specific heat capacity Cp (KJ/KgK)** |
|---|---|---|---|---|---|
| Asphalt membrane | 0,005 | 0,23 | 0,022 | 1800 | 1.00 |
| Concrete 1800 kg / $m^3$ | 0,100 | 1,15 | 0,087 | 1900 | 1.00 |
| Reinforced concrete with 2% steel | 0,150 | 2,50 | 0,060 | 2400 | 1.00 |
| Internal surface thermal resistance **Rsi** | | | 0,100 | | |
| External surface thermal resistance **Rse** | | | 0,040 | | |
| **Thermal transmittance** | **U value** | **3,239** | **$W/m^2$ K** | **Thermal mass Cm ($kJ/m^2K$)** | **240** |

Table 11.18. Table of materials and characteristics of the internal floor of the typical classroom in its current condition, for the calculation of the thermal transmittance coefficient of the internal floor.

| **Materials Internal Floor** | **Thickness d (m)** | **Thermal conductivity λ (W/mK)** | **Thermal Resistance R ($m^2K/W$)** | **Density ρ ($kg/m^3$)** | **Specific heat capacity Cp (KJ/KgK)** |
|---|---|---|---|---|---|
| Mosaic floor | 0,030 | 1,30 | 0,032 | 2300 | 1.00 |
| Concrete 1800 kg / $m^3$ | 0,100 | 1,15 | 0,087 | 1800 | 1.00 |
| Reinforced concrete with 2% steel | 0,150 | 2,50 | 0,060 | 2400 | 1.00 |
| Internal surface thermal resistance **Rsi** | | | 0,170 | | |
| External surface thermal resistance **Rse** | | | 0,170 | | |
| **Thermal transmittance** | **U value** | **1,961** | **$W/m^2$ K** | **Thermal mass Cm ($kJ/m^2K$)** | **183.96** |

Table 11.19. Table of materials and characteristics of the ground floor of the typical classroom in its current condition, for the calculation of the thermal transmittance coefficient of the ground floor.

| **Materials Ground Floor** | **Thickness d (m)** | **Thermal conductivity λ (W/mK)** | **Thermal Resistance R ($m^2K/W$)** | **Density ρ ($kg/m^3$)** | **Specific heat capacity Cp (KJ/KgK)** |
|---|---|---|---|---|---|
| Mosaic floor | 0,030 | 1,30 | 0,032 | 2300 | 1.00 |
| Concrete 1800 kg / $m^3$ | 0,100 | 1,15 | 0,087 | 1800 | 1.00 |
| Reinforced concrete with 2% steel | 0,150 | 2,50 | 0,060 | 2400 | 1.00 |
| Internal surface thermal resistance **Rsi** | | | 0,170 | | |
| External surface thermal resistance **Rse** | | | 0,00 | | |
| **Thermal transmittance** | **U value** | **2,083** | $W/m^2 K$ | **Thermal mass Cm ($kJ/m^2K$)** | **195** |

The methodology proposed in the Building Thermal Insulation Guide was used to calculate the thermal transmittance coefficient of openings (doors and windows) of the typical classroom in its current condition [451]. The standard classroom had single aluminium frames without a thermal break, and with a frame thermal transmittance coefficient of Uf = 7.0 $W/m^2K$. The glass panes were single, 6 mm thick (e = 0.89), without low-emissivity layer, with glass thermal transmittance, Ug = 5.7 $W/m^2K$. Based on the above data for vertical frames with frame area ≤25% in relation to the total area of the frame, the external frames of the standard classroom in its current condition have a window thermal transmittance of U = 6.0 $W/m^2K$. The g-value of the glass is 0.82.

### *11.4.2.4. Internal loads and schedules*

Internal gains have a considerable impact on thermal and energy performance [452]. Therefore, people, internal lights, equipment, and plug-loads were defined as internal gains following realistic schedules. The study considered the internal heat gains produced by people and artificial lighting as they directly influence the indoor environment. Specifically, lighting is provided by florescent lamp luminaires with maximum sensible gain of $10W/m^2$ and 20 people were included in the simulation with 78W/p of maximum sensible gain and 40W/p of maximum latent gain (EN 17772-1:2017) [453]. The occupancy and operational schedules followed the on-site recording for each climatic period. Modelling natural ventilation depends on observation, questionnaires and assumptions, as it is highly unlikely a modeller can accurately determine when and which windows will be opened, and for what length of time. Based on field observation and questionnaires (see results in **Chapter 14.3.6 and Chapter 16.2.1**) windows were opened during all occupied hours during the summer (07:30-13:35), only at three break-intervals (20mins) during winter and from 09:00 to 13:35 during the intermediate period. Table 11.20 shows the occupancy profile, as well as window operation throughout the year.

Table 11.20. Window operation and occupancy

| Schedule and Occupancy | | Window (single sided ventilation) | | |
|---|---|---|---|---|
| | | Interim (mid- April to mid-May and October to mid-November) | Summer (mid-May to October) | Winter (mid-November to mid-April) |
| **07:30-09:00** | 1 | 0 | 1 | 0 |
| **25 min break** | 0 | 1 | 1 | 1 |
| **09:25-10:55** | 1 | 1 | 1 | 0 |
| **15 min break** | 0 | 1 | 1 | 1 |
| **11:10- 12:40** | 1 | 1 | 1 | 0 |
| **10 min break** | 0 | 1 | 1 | 1 |
| **12:50-13:35** | 1 | 1 | 1 | 0 |
| **13.35-07:30** | 0 | 0 | 0 | 0 |
| 0: occupancy off, 1: occupancy on; 0: windows closed, 1: windows opened | | | | |

*11.4.2.5. Technical systems*

For the **first and second stage** of the analysis, no technical system was included in the modelling in order to examine the thermal performance of the building envelope in the actual conditions. For the **third and fourth stage**, technical systems were included in order to analyse the cost effectiveness of adaptation measures. For heating system, a diesel-heated boiler system with seasonal energy efficiency 0.92 was used, which is the typical and most conventional system widely used in educational buildings in Cyprus. For cooling, based on the technical specifications provided by the Ministry of Education, Culture, Sports and Youth, in the case of installation of air conditioning this will be wall-mounted, air-cooled, split type heat pump with minimum seasonal energy efficiency ratio (SEER) of 5.6. For the needs of the present study, a system with seasonal energy efficiency ratio of 6 was selected. Based on EN 15251:2007, the default design values of the indoor operative temperature in classrooms in winter and summer for buildings with mechanical systems for buildings in Category II is 20°C and 26°C respectively. The set points were set based on the aforementioned standard and applied during the occupied time. Table 11.21 summarizes the operation characteristics of technical systems.

Table 11.21. Technical system operation

| Parameter | Operation | Reference |
|---|---|---|
| **Operation period of technical systems** | 5 days per week from 07:30 to 13:35 | With regards to local usage pattern |
| **Heating period** | October to April (15days of Christmas and 15days of Easter breaks excluded) | With regards to local climatic conditions |
| **Required temperature during the operation hours for the heating period** | 20 °C | EN 15251:2007, Category II |

| | | |
|---|---|---|
| **Cooling period** | May to November | With regards to local climatic conditions |
| **Required temperature during the operation hours for the cooling period** | 26 °C | EN 15251:2007, Category II |

*11.4.2.6. Model validation: Simulation vs measured data*

In order to validate the model, from December 2017 to September 2018 detailed external temperature monitoring (as described in **Chapter 11.2)** was obtained and were imported to the weather file in order to assess the classroom under the same external conditions. The data were compared on hourly intervals across the entire year.

The validation analysis of indoor conditions was performed in a classroom with only its roof exposed to the outside environment. In order to evaluate the accuracy of the model, the root mean square error (RMSE) of prediction, between measured and predicted values, was defined for three different periods (summer, intermediate and winter). Specifically, the assessment took place for the 21-25$^{th}$ of May 2018, the 6-9$^{th}$ of April 2018, and 10-12$^{th}$ of February 2018. It is interesting to mention that in order to eliminate the affection of technical system during the heating period the validation took place during the weekend. In order to assess reliably the model's quality, the study employed the distribution characteristics of the prediction error, i.e., the mean absolute error (MAE) and the standard deviation of MAE (MAESD). The findings indicate that the simulation tool is fairly accurate and credible when it comes to the prediction of the thermal conditions indoors. The error analysis is summarized in Table 11.22. Apparently, RMSE=0 is the perfect prediction case. During the summer period, the validation showed almost a perfect match of measured and simulated temperatures. During the winter period, as mentioned the validation took place during weekend to avoid technical system that is provided during weekdays. Because the classrooms are supported by technical heating during weekdays in real time, that may affected the results and thus a small differentiation is appeared between measures and simulated results. During the intermediate period, the validation shows the highest differentiation compare to other seasons probably due to other factors that were not controlled by the user. As shown, the RMSE is very small, ranging from 0.062°C to 0.079°C in all periods. The values for the mean absolute error are below 0.4 °C during both winter and summer period and around 0.7°C during the intermediate period with standard deviation ranging between 0.26-0.32°C, confirming the good predicting quality.

Figures 11.8-11.10 show the measured and predicted indoor air temperature in a selected periods during the occupied period. RMSE was calculated using the equation:

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n}(x_{pr_i} - x_{m_i})^2}}{n} \qquad \text{(Eq.11.9)}$$

where $x_{pr_i}$ and $x_{m_i}$ are the predicted and measured temperatures at time $i$, respectively, and $n$ the total number of data sets.

Assessing reliably the model's quality entailed the use of the distribution characteristics of the prediction error, i.e., the mean absolute error (MAE) and the standard deviation of MAE (MAESD) calculated by the following equations:

$$MAE = \frac{\sum_{i=1}^{n}\left|x_{pr_i} - x_{m_i}\right|}{n} \qquad \text{(Eq.11.10)}$$

$$MAE_{SD} = \sqrt{\frac{\sum_{i=1}^{n}(\left|x_{pr_i} - x_{m_i}\right| - MAE)^2}{n-1}} \qquad \text{(Eq.11.11)}$$

Table 11.22. Error analysis indexes

| | Summer | Intermediate | Winter |
|---|---|---|---|
| **RMSE** | 0.064 | 0.079 | 0.062 |
| **MAE** | 0.295 | 0.704 | 0.367 |
| **MAEsd** | 0.260 | 0.324 | 0.282 |

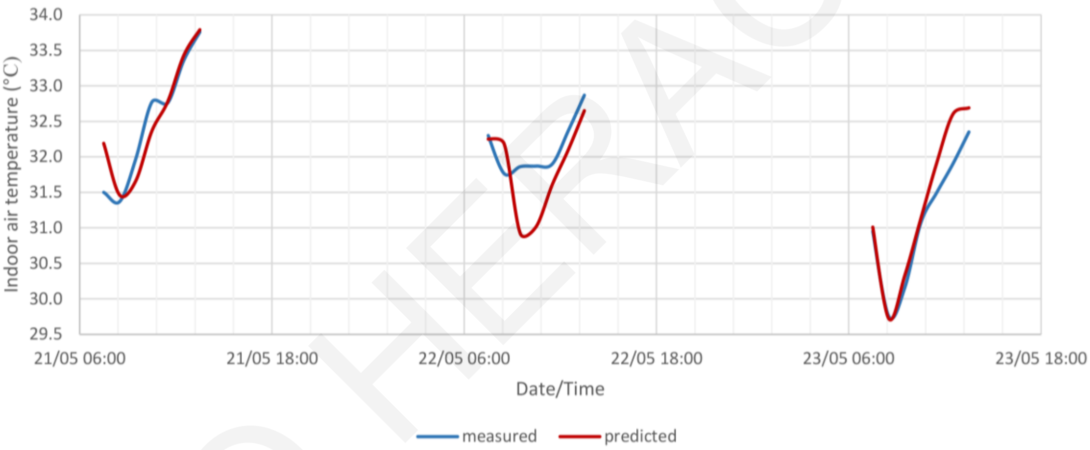



Figure 11.8. Comparison of simulated and measured air temperature hourly data during the occupied period (07:30-13:35) in May 2018.

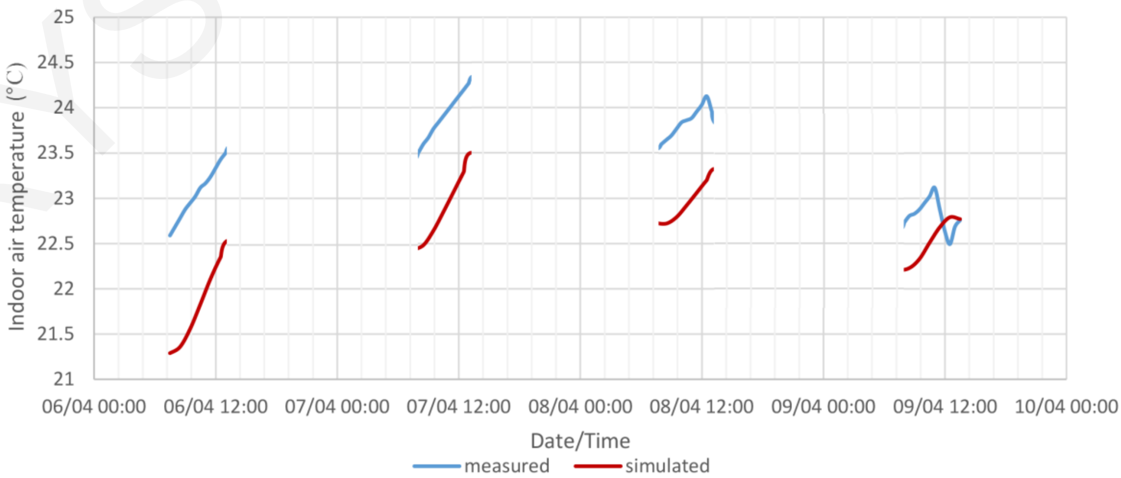



Figure 11.9. Comparison of simulated and measured air temperature hourly data during the occupied period (07:30-13:35) in April.

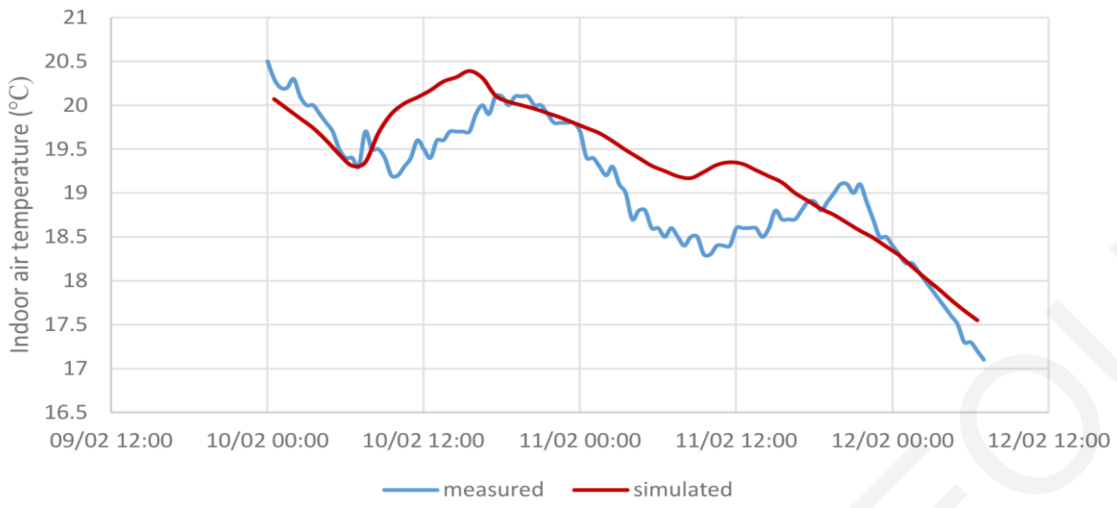



Figure 11.10. Comparison of simulated and measured air temperature hourly data during the weekend (00:00-24:00) in February to avoid technical systems.

The same model was used to assess proposed adaptation measures for improved thermal comfort and energy performance upgrade under current and future climatic conditions.

### *11.4.3. Climatic scenarios*

For the assessment of thermal and energy performance of educational buildings under the future climatic conditions, the future climate of scenario A1B for 2050 and 2090 was downloaded from Meteonorm v.7.1.11. The choice of the climatic scenario was based on the intermediate case, which lies in the middle of the 'business as usual' scenario and the 'united sustainable planet' extremes [6]. The A1B scenario was well adjusted for the study purposes and is in line with the claims of the present study by large. The TMY refers to the period 2000-2009 for temperature and to the period 1991-2010 for radiation. Moreover, it would be interesting to note that if the building fails in the intermediate case, it fails higher in a more extreme climate projection.

The results of climate prediction for TMY, 2050, 2090 and for the acceptable adaptive thermal comfort zone are presented in this section. More specifically, the annual average values of air temperature is predicted to rise in the future and specifically increase by 0.7°C and 1.7°C for 2050 and 2090 respectively. The average relative humidity will increase by 10% in both 2050 and 2090, the average solar radiation will increase by 5W/m$^2$, while the wind speed does not show significant variations compared to the TMY. Table 11.23 shows the annual average values for environmental parameters.

Table 11.23. Annual average values of certain climatic parameters in Nicosia for TMY, 2050 and 2090 under the scenario A1B.

| Nicosia | TMY | | | 2050 (A1B) | | | 2090 (A1B) | | |
|---|---|---|---|---|---|---|---|---|---|
| | min | average | max | min | average | max | min | average | max |
| **Dry-Bulb Temperature (°C)** | 2.8 | 19.9 | 37.6 | 3.8 | 20.6 | 38.0 | 4.6 | 21.6 | 39.3 |
| **Relative Humidity (%)** | 32 | 66.5 | 100.0 | 39.0 | 76.3 | 100.0 | 39.0 | 76.3 | 100.0 |
| **Solar Radiation (W/m$^2$)** | 0 | 205.7 | 1048.0 | 0.0 | 209.8 | 1068.0 | 0.0 | 211.3 | 1068.0 |
| **Wind Speed (m/s)** | 0 | 2.8 | 15.0 | 0.0 | 3.2 | 16.1 | 0.0 | 3.2 | 16.1 |

Figure 11.11 shows the temperature distribution of all months during the TMY, 2050 and 2090 using the box and whisker plots in order to identify the mean, the maximum, the minimum and the median values of each month.

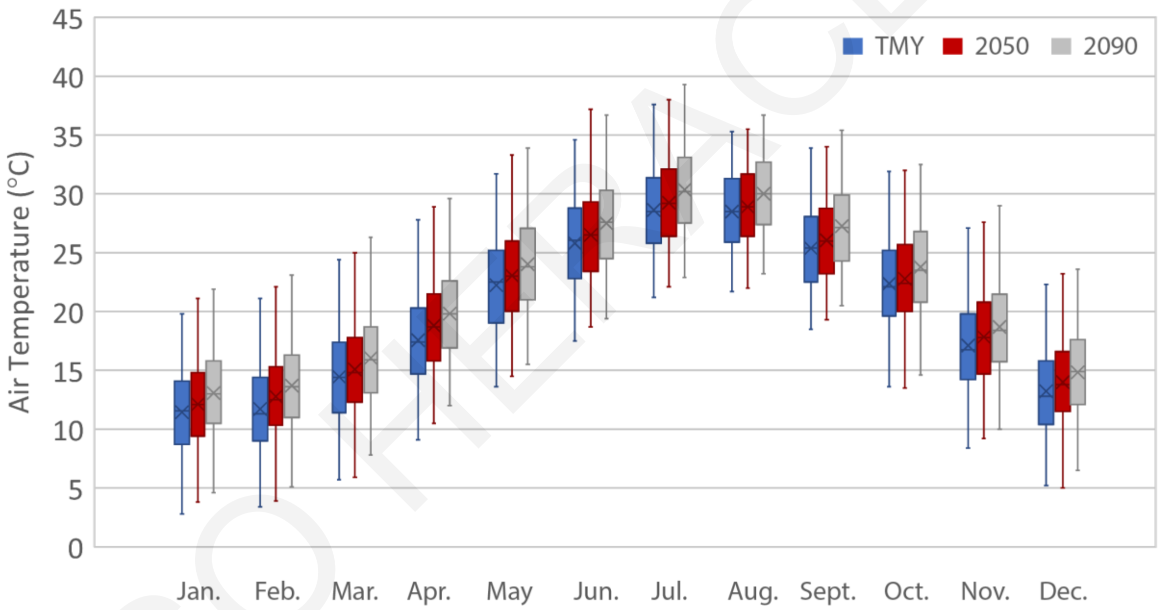



Figure 11.11. Monthly temperature distribution for TMY, 2050 and 2090 exported from Meteonorm.

Figure 11.12 illustrates the monthly temperature difference for air mean, minimum and maximum air temperatures between the TMY and 2050 and 2090. As observed, the highest increase occurred in spring between 2°C and 2.5°C in average values and between 2°C and 3°C in maximum temperatures. In addition, the average minimum air temperature will increase by about 1.5 to 3°C leading to warmer nights in the future.

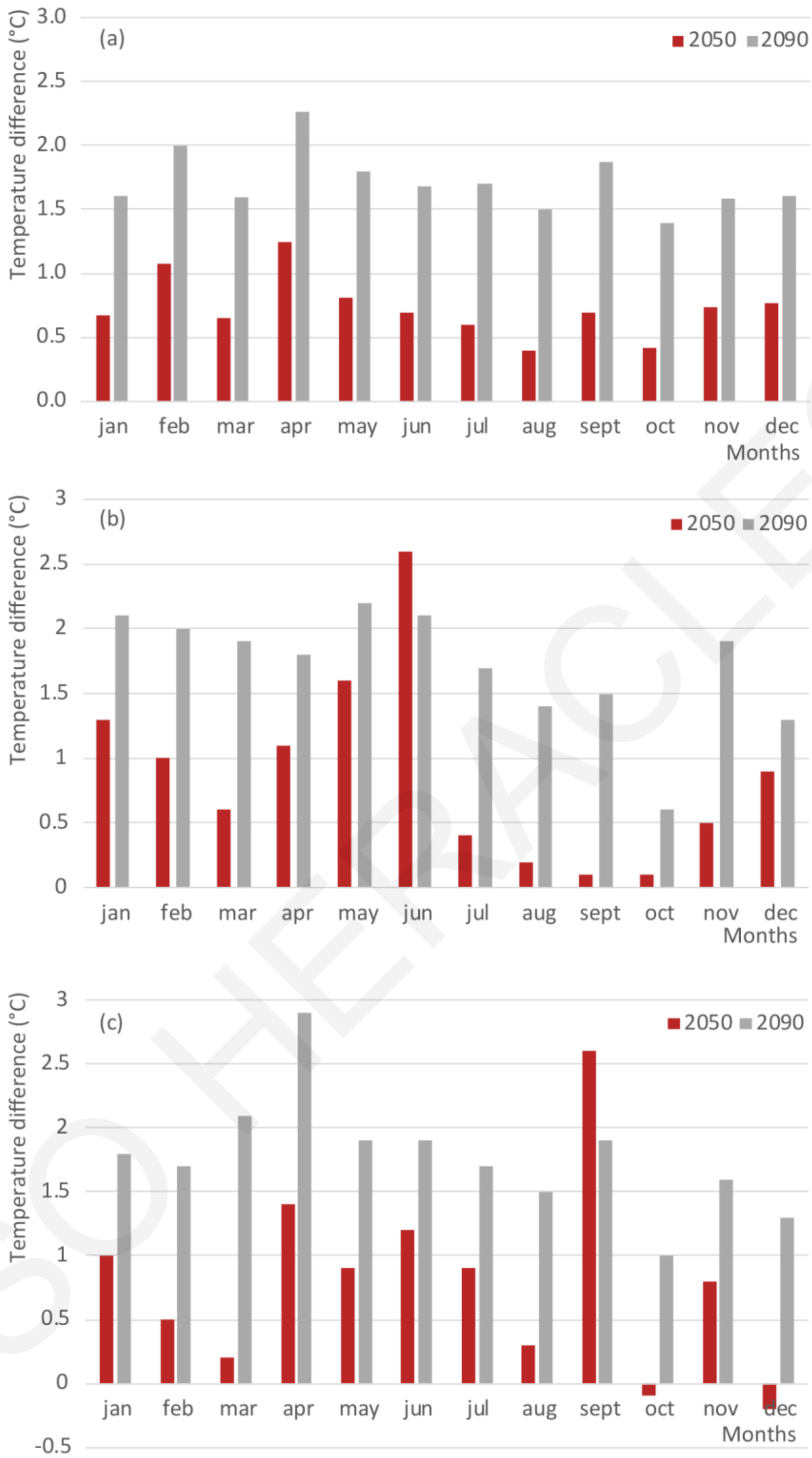



Figure 11.12. Temperature difference of the (a) mean (b) maximum and (c) minimum air temperature between monthly average in TMY and monthly average in 2050 and 2090.

For the assessment of the thermal comfort zone, two representative months, namely, June (summer) and January (winter), were selected for demonstration (Table 11.12):

- For January of TMY, the minimum, maximum, and average temperatures are 2.8°C, 18.8°C and 11.5°C respectively, and the thermal comfort zone for the 80% acceptability based on EN 15251:2007[87] ranges between 19.6-25.6°C.

- For January of 2050, the minimum, maximum, and average temperatures are 3.8°C, 21.1°C and 12.1°C respectively, and the thermal comfort zone for the 80% acceptability ranges between 19.8-25.8°C.
- For January of 2090, the minimum, maximum, and average temperatures are 4.6°C, 21.9°C and 13.1°C respectively, and the thermal comfort zone for the 80% acceptability ranges between 20.1-26.1°C.
- For June of TMY, the minimum, maximum, and average temperatures are 17.5°C, 34.6°C and 28.6°C respectively, and the thermal comfort zone for the 80% acceptability ranges between 24.3-30.3°C.
- For June of 2050, the minimum, maximum, and average temperatures are 18.7°C, 37.2°C and 29.2°C respectively, and the thermal comfort zone for the 80% acceptability ranges between 24.5-30.5°C.
- For June of 2090, the minimum, maximum, and average temperatures are 19.4°C, 36.7°C and 30.3°C respectively, and the thermal comfort zone for the 80% acceptability ranges between 24.9-30.9°C.

As shown, the thermal comfort zone shifts to higher temperatures as years progress and particularly by about 0.6°C in 2090 (Table 11.24).

Table 11.24. Minimum, maximum and mean air temperature of Nicosia for January and June and calculation of thermal comfort zone for the 80% acceptability based on EN 15251:2007 for TMY, 2050, 2090.

| | TMY | | | | 2050 | | | | 2090 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Min** | **Max** | **Mean** | **Comfort zone** | **Min** | **Max** | **Mean** | **Comfort zone** | **Min** | **Max** | **Mean** | **Comfort zone** |
| **Jan.** | 2.8 | 19.8 | 11.5 | 19.6-25.6 | 3.8 | 21.1 | 12.1 | 19.8-25.8 | 4.6 | 21.9 | 13.1 | 20.1-26.1 |
| **June** | 17.5 | 34.6 | 28.6 | 24.3-30.3 | 18.7 | 37.2 | 29.2 | 24.5-30.5 | 19.4 | 36.7 | 30.3 | 24.9-30.9 |

### *11.4.4. Proposed scenarios of natural ventilation for the minimization of overheating risk*

The examination of the impact of natural ventilation on the minimization of the overheating risk of educational buildings (between May and September) was also undertaken using dynamic simulation for the typical meteorological year, the 2050 and 2090. Four typical classrooms of general education, one in each orientation, were selected for in-depth analysis. The model was built in IES-VE as described in **Chapter 11.4.2**.

The investigation has shed light to possible improvements relating to different ventilation strategies. The strategies concerned include: (a) night ventilation alone (b) night ventilation combined with the current daytime ventilation (c) night ventilation combined with daytime ventilation only during break-time in the summer and (d) full-day ventilation (24h). For the abovementioned scenarios, all windows of the classroom remained wide open, i.e. C, F, H, J and M remaining fully open (creating cross ventilation) while the door remained closed. For the cases of night ventilation alone (Case 1) and night ventilation combined with daytime ventilation during break-time (Case 2), the door remained open during teaching time. Despite the high infiltration rate of the classrooms, i.e., 4 air change per hour (ach), this measure is deemed necessary in order to ensure air quality in the indoor spaces, providing fresh air of at least 3 l/s per person. More specifically, keeping the door open ensures fresh air at a minimum rate of 8 l/s per person, thus achieving $CO_2$ concentrations below 1000ppm. During the "night ventilation alone" strategy, the windows were open from 21:00 to 07:00. During the "night ventilation combined with the current daytime ventilation" strategy, the windows were open from 21:00 to 07:00 and from 07:00 to 12:50 during the summer. During the "night ventilation combined with daytime ventilation only during recess" strategy, the windows were open from 21:00 to 07:00 , from 09:00 to 09:25, from 10:55 to 11:10 , and from 12:40 to 12:50 to ensure indoor air quality. During full-day ventilation, the windows remained open for 24 hours (Table 11.25).

The proposed scenarios were investigated under the current climatic conditions and then under the climate change projections in all orientations of classrooms.

Table 11.25. Proposed window operation.

| Window operation during summer period (May-September) | | |
|---|---|---|
| **Reference** | Daytime ventilation only | 07:30-12:50 |
| **Case 1** | Night ventilation alone | 21:00-07:00 |
| **Case 2** | Night ventilation combined with daytime ventilation only during recess | 21:00-07:00<br>09:00-09:25<br>10:55-11:10<br>12:40- 12:5 |
| **Case 3** | Night ventilation combined with the current daytime ventilation | 21:00-07:00<br>07:30-12:50 |
| **Case 4** | Full-day ventilation (24h) | 00:00-24:00 |

### *11.4.5. Adaptation measures for improved thermal comfort*

Based on the weaknesses identified in existing educational building, a number of possible solutions could be suggested for improving thermal comfort and reducing energy consumption in these premises, taking into account the local context. The south oriented classrooms were further remodeled on the basis of the suggested retrofitting solutions. Moreover, a new simulations have been performed, using the same user behaviour profiles. The retrofitting solutions include thermal properties and construction detailing of buildings, the geometry of solar shading systems, operational concerns and mild retrofitting systems. Initially, each parameter is examined individually, keeping other components unchanged, followed by the consideration of their cumulative effect.

Adaptation measures for improved thermal and energy performance of buildings are analysed in two stages, one without the support of a technical system in order to identify the actual behaviour of the building, and the other one with the provision of a technical system to calculate the cost-effectiveness of proposed interventions. Both stages use the same adaptation measures for analysis. The analysis undertaken in the first stage is a preliminary analysis in order to proceed to the second stage and to calculate the cost-effectiveness of adaptation measures. Combinations in the first stage, where no technical systems are provided, are mostly based on energy performances and aim to identify the contribution of individual investigations, adding a new strategy each time. Combinations in stage two, where technical systems are included, are based on the optimal cases of previous examinations in terms of the cost effectiveness and include ten different retrofit scenarios taking into account the difficulty of installation.  Selected scenarios for second stage analysis are described in detail in a following section, i.e. **Chapter 11.4.6**.

Below the adaptation measures in educational buildings are presented for the analysis of the first stage that are not covered by technical systems.

### *11.4.5.1. Construction interventions*

Thermal insulation of the building envelope (wall, roof, floor, windows) aims to protect the building envelope from external climatic conditions, both during the winter and the summer and provide satisfactory levels of thermal comfort. Additionally, thermal insulation aims to improve energy performance of educational buildings and consequently reduce the $CO_2$ emissions. The construction interventions on the building envelope refer to thermal insulation on the walls, roof, floor and replacement of single glazing windows with relatively high-performance window systems.

#### *11.4.5.1.1. New layer of exterior insulation on the walls*

To improve the energy performance and comfort conditions of the typical classroom, the thermal insulation of the wall is investigated through scenarios of different insulation thicknesses. The external installation of 50 mm - 150 mm of rockwool insulation with λ=0,032 W/mK recommended for investigation. External insulation is proposed in order to maintain the thermal mass inside the building through the brick wall, including the structure from reinforced concrete. Table 11.26 shows the U-value of Cases 1-4 (C1-C4) which examine new layers of exterior insulation on the walls. The thermal transmittance coefficients of proposed external walls, except the one with 5cm insulation, satisfy the provision of the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020 onwards, which determines U ≤0,4 W/m$^2$K as a maximum allowed value for the external walls which are part of the building envelope.

Table 11.26. Scenarios regarding a new layer of insulation on the walls.

| Refurbishment strategies | | | | | Retrofit option |
|---|---|---|---|---|---|
| **Building envelope properties** | New layer of exterior insulation on the walls | 5 cm | U- value (W/m$^2$K) | 0.43 | C1 |
| | | 8 cm | U- value (W/m$^2$K) | 0.31 | C2 |
| | | 10 cm | U- value (W/m$^2$K) | 0.26 | C3 |
| | | 15 cm | U- value (W/m$^2$K) | 0.18 | C4 |

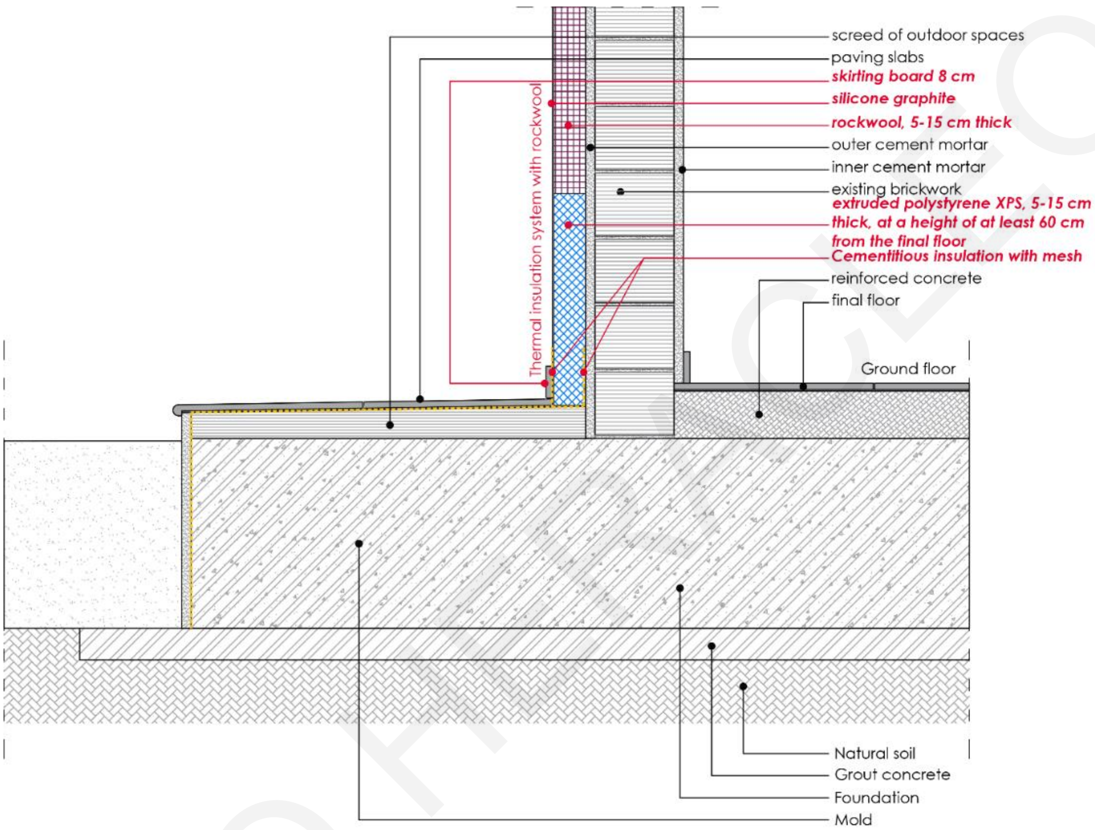



Figure 11.13. Construction detail of external wall including thermal insulation.

*11.4.5.1.2. New layer of exterior insulation on the roof*

To improve the energy performance and comfort conditions of the typical classroom, the thermal insulation of the roof was investigated through scenarios of different insulation thicknesses. The external installation of 50 mm - 200 mm of extruded polystyrene with λ=0,032 W/mK recommended for investigation for a dry installation. In addition, pavement slabs will be installed. The use of pavement slabs prevents the movement of thermal insulation due to the wind and floating due to water as well as is protecting it from damage. Table 11.27 shows the U-value of Cases 5-8 (C5-C8) which examine the addition of a new layer of exterior insulation on the roof. The thermal transmittance coefficients of the proposed external roof, except the one with 5cm insulation, satisfy the provision of the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020 onwards, which determines U ≤0,4 W/m$^2$K as a maximum allowed value for the external horizontal elements such as a roof which are part of the building envelope.

Table 11.27. Scenarios regarding a new layer of insulation on the roof.

| Refurbishment strategies | | | | | Retrofit option |
|---|---|---|---|---|---|
| **Building envelope properties** | New layer of insulation on the roof | 5 cm | U- value (W/m²K) | 0.53 | C5 |
| | | 10 cm | U- value (W/m²K) | 0.29 | C6 |
| | | 15 cm | U- value (W/m²K) | 0.19 | C7 |
| | | 20 cm | U- value (W/m²K) | 0.15 | C8 |

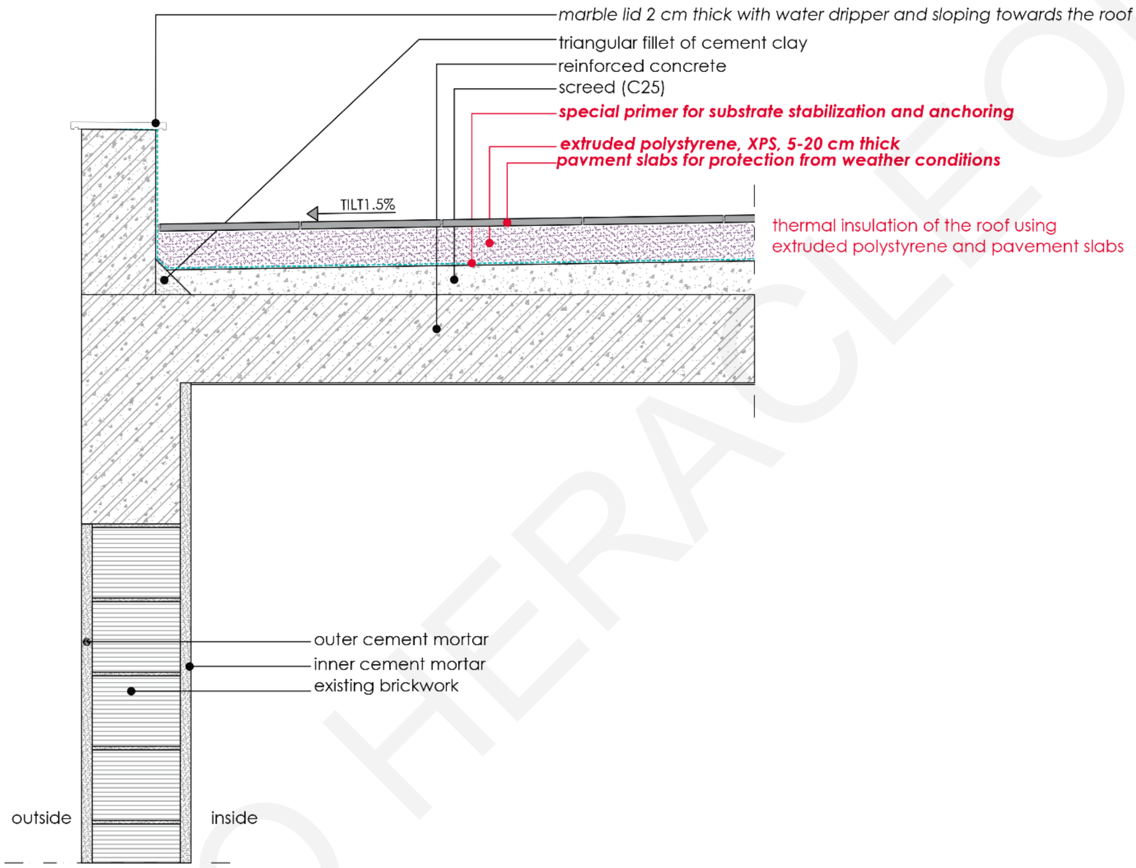



Figure 11.14. Construction detail of external roof including thermal insulation.

*11.4.5.1.3. New layer of insulation on the floor*

To improve the energy performance and comfort conditions of the typical classroom, the thermal insulation of the floor was investigated through scenarios of different insulation thicknesses. The installation of 50 mm - 100 mm of extruded polystyrene with λ=0,032 W/mK recommended for investigation for a dry installation. In addition, a screed with lightweight concrete and the top tiles are added. Table 11.28 shows the U-value of Cases 9-11 (C9-C11) which examine a new layer of exterior insulation on the floor. The Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020 onwards, do not define maximum allowed value for the floor in contact with the ground.

Table 11.28. Scenarios regarding new layer of insulation on the floor.

| Refurbishment strategies | | | | | Retrofit option |
|---|---|---|---|---|---|
| **Building envelope properties** | New layer of insulation on the floor | 5 cm | U- value (W/m$^2$K) | 0.5 | C9 |
| | | 8 cm | U- value (W/m$^2$K) | 0.35 | C10 |
| | | 10 cm | U- value (W/m$^2$K) | 0.29 | C11 |

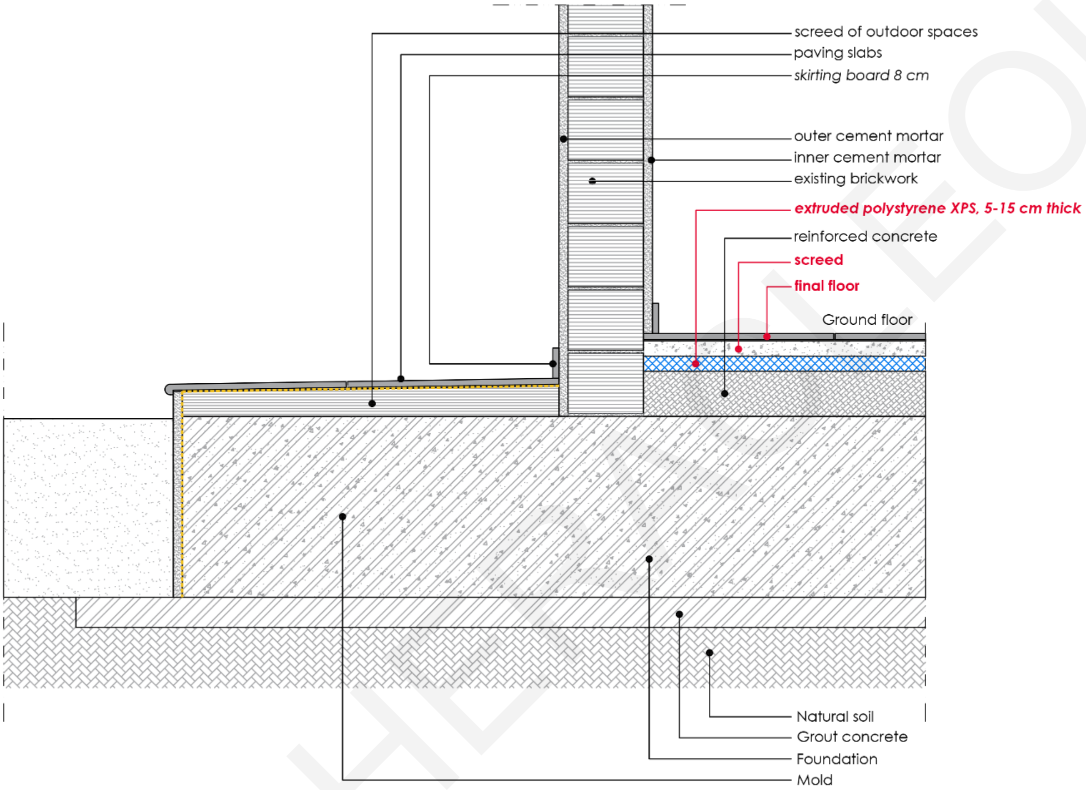



Figure 11.15. Construction detail of floor in contact with ground including thermal insulation.

*11.4.5.1.4. Replacement of existing windows with relatively high-performance glazing systems and window frames*

To improve the energy performance and comfort conditions of the typical classroom, the existing windows with single glass should be replaced with relatively high-performance glazing systems and window frames. The proposed solutions include:

(a) Double glazing of 4mm thick with an air gap of 15mm with low heat emission coating ($\varepsilon \leq 0.15$) on one side (low-emissivity layer) and standard frame;

(b) Double glazing of 4mm thick with an air gap of 15mm with low heat emission coating ($\varepsilon \leq 0.15$) on one side (low-emissivity layer) and insulated frame, no.1;

(c) Double glazing of 4mm thick with an air gap of 15mm with low heat emission coating ($\varepsilon \leq 0.15$) on one side (low-emissivity layer) and insulated frame, no2; and

(d) triple glazing of 4mm thick with an air gap of 10mm with low heat emission coating ($\varepsilon \leq 0.15$) on one side (low-emissivity layer) and insulated frame.

Table 11.29 shows the U-value of Cases 13-15 (C13-C15) which examine new layer of exterior insulation on the proposed windows. The thermal transmittance coefficients of proposed windows, except the double low-e and standard aluminium frame as well as double low-e glazing with insulated frame no.1, satisfy the provision of Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020 onwards, which determines U ≤2,25 W/m$^2$K as a maximum allowed value for the windows which are part of the building envelope.

Table 11.29. Scenarios for replacement of existing windows.

| Refurbishment strategies | | | | | Retrofit option |
|---|---|---|---|---|---|
| Building envelope properties | Replacement of existing windows with relatively high-performance glazing systems and window frames | double low-e glazing, standard frame | U-value frame (W/m$^2$K) | 5.8 | C12 |
| | | | U-value glaze (W/m$^2$K) | 1.3 | |
| | | | g-value | 0.7 | |
| | | | U-value window (W/m2K) | 3.5 | |
| | | double low-e glazing, insulated frame no.1 | U-value frame (W/m$^2$K) | 4.5 | C13 |
| | | | U-value glaze (W/m$^2$K) | 1.3 | |
| | | | g-value | 0.6 | |
| | | | U-value window (W/m$^2$K) | 2.7 | |
| | | double low-e glazing, insulated frame no.2 | U-value frame (W/m$^2$K) | 2.6 | C14 |
| | | | U-value glaze (W/m$^2$K) | 1.3 | |
| | | | g-value | 0.6 | |
| | | | U-value window (W/m$^2$K) | 2.2 | |
| | | triple glazing, insulated frame | U-value frame (W/m$^2$K) | 2.6 | C15 |
| | | | U-value glaze (W/m$^2$K) | 1 | |
| | | | g-value | 0.5 | |
| | | | U-value window (W/m$^2$K) | 1.3 | |

### *11.4.5.2. Natural ventilation*

The characteristics of the Mediterranean climate make natural ventilation a particularly effective strategy for improving thermal comfort conditions especially for the summer season. The usual operation of windows in classrooms is single-sided ventilation from 07:30-13:30. Different ventilation strategies were proposed based on the results of the experimental procedure on site for proper operation of windows (please see **Chapter 15.2**). To improve thermal comfort and energy performance of classrooms, the ventilation rate should be increased in the summer to remove the unwanted stored heat from the building envelope, once the external conditions allow it. Based on the literature, ventilation is most appropriate where the air temperature and humidity fall within comfort limits. Taking into account that the environmental climatic conditions of the Mediterranean region are characterized by high daily fluctuations, night ventilation is deemed as an effective passive cooling method. The examined scenarios consider a manual operation of windows for cross ventilation during daytime (07:30-13:30), cross ventilation during daytime (07:30-13:30) and nighttime (21:00-07:30) and cross ventilation only during nighttime (21:00-07:30). Cross ventilation is achieved having openings C, F, H, J and M fully opened. Table 11.30 shows the different scenarios for increasing the ventilation rate in the summer (Case 16- Case 18).

Table 11.30. Scenarios for window operation.

| Refurbishment strategies | | | Retrofit option |
|---|---|---|---|
| **Natural ventilation** | Increasing ventilation rate in summer (mid-May to October) | cross ventilation during daytime (07:30-13:30) | C16 |
| | | cross ventilation during daytime (07:30-13:30) and night-time (21:00-07:30) | C17 |
| | | cross ventilation only during night-time (21:00-07:30) | C18 |

It is worth mentioning that for the needs of the calculation of the cost-effectiveness (**Chapter 11.4.6** and **Chapter 15.3.3**) and for safety reasons associated with the openings of windows during nighttime, a ventilator that closely imitates the window operation was selected as another simulation option based on the results of the simulation. This ventilator uses its fan for air extraction and has an efficiency of 1000 l/s, i.e. 3600$m^3$/h.

*11.4.5.3. Architectural interventions*

Protecting glazed surfaces from the sun is essential to ensure thermal comfort during the cooling period. According to the literature [384], [388], more suitable sun protection of the southern openings is achieved by the use of horizontal overhang or blinds, while for the eastern and western openings by the use of vertical blinds, awnings or grids. It should be noted that south-oriented classrooms already have an overhang of 2m width therefore the following shading devices are considered for investigation: (a) increase overhang by 20 cm (b) use three fixed horizontal louvers of 5cm height with an air gap of 25 cm and solar emissivity of 0.6 and (c) use of external movable horizontal louvers with daytime/night-time resistance: 0.1 $m^2K/W$ with the shutters always closed during the winter nights (18:00-07:00), to minimize heat losses, and, in summer they remain closed during daytime (07:00-18:00) so as to avoid overheating. Table 11.31 show the proposed shading devices for the reduction of heat gains (Case 19- Case 21).

Table 11.31. Scenarios for architectural interventions.

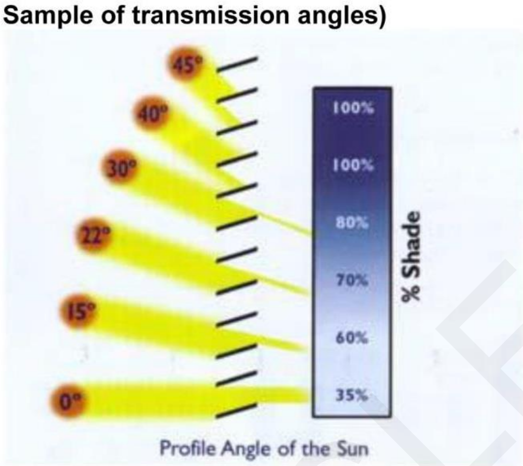
| Refurbishment strategies | | | Retrofit option |
|---|---|---|---|
| **Geometry** | Shading devices | Increase overhang by 20cm | C19 |
| | | horizontal louvers 25-5-25-5-25-5<br>solar emissivity: 0.9 | C20 |
| | | external movable horizontal louvers<br>solar emissivity: 0.9<br>daytime/night-time resistance: 0.1 $m^2K/W$ | C21 |

Transmission factor: 0°=0.65, 15°=0.40, 30°=0.20, 45°=0, 60°=0, 75°=0, 90°=0,

Operation: Winter: 18:00 - 07:00

Summer: 07:00 - 18:00

**Sample of transmission angles)**



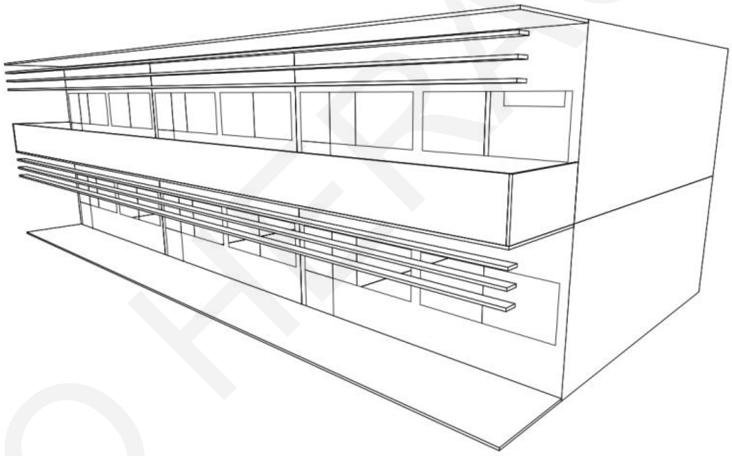



Figure 11.16. 3D perspective sketch of horizontal louvers (Case 20).

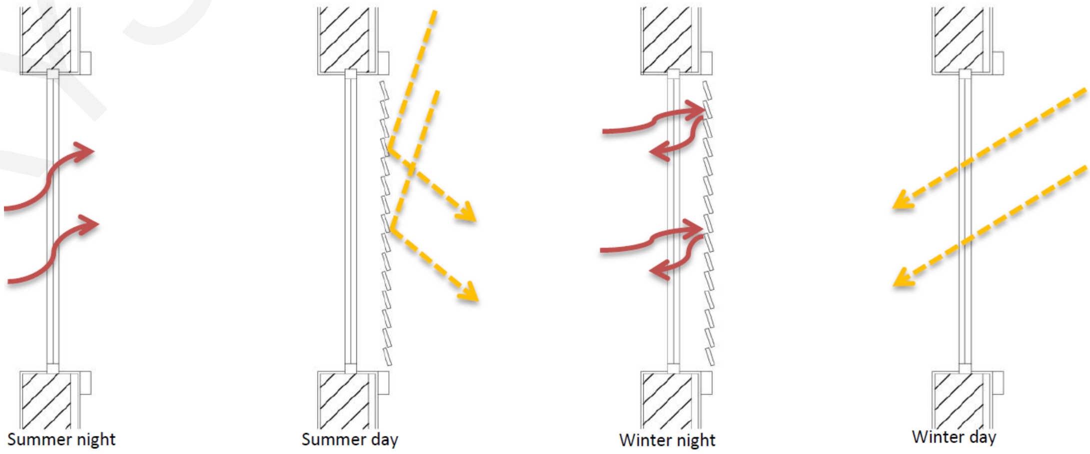



Figure 11.17. Construction detail and operation of external movable horizontal louvers (Case 21).

*11.4.5.4. Mechanical ventilation system*

Heat recovery ventilation decreases the heat loss from ventilation dramatically during winter, and hence the hours of discomfort; as it provides controlled ventilation and ensures the required air exchange in order to maintain indoor air quality. The installation of a **heat recovery ventilation system** has been chosen as ventilation system, through which the heating and cooling will be assisted, since the incoming air will have 70% of the indoor temperature. As for cooling, only the alternator system can reverse the switching process (by reversing the roles of the fans) or cancel it completely so that the building is discharged at night from the heat stored during the day. Specifically, the lowest ventilation rate of 8 l/s/person for schools is considered for the selection of the units in order to maintain indoor air quality. The single unit can be operated as an air to air exchanger with an efficiency of 200 l/s (i.e. 720 $m^3/h$). The system operates always during the occupied period of 07:30-13:35 throughout the school year, while during the summer period it is also on between 00:00-07:30 and 13:35-24:00 when outdoor air temperature is < 31°C and outdoor relative humidity is <70% to reduce the thermal loads of the building envelope. Table 11.32 shows the characteristics of the mechanical ventilation (Case 22).

Table 11.32. Scenario for mechanical ventilation.

| Refurbishment strategies | | | Retrofit option |
|---|---|---|---|
| **Mechanical ventilation with heat recovery (MVHR)** | Heat recovery ventilation system (200l/s) | Operation: Winter: 07:30-13:35 on<br>Summer: 07:30-13:35 on,<br>00:00-07:30 and 13:35-24:00<br>on when outdoor air temperature is < 31°C and outdoor relative humidity is <70% | C22 |

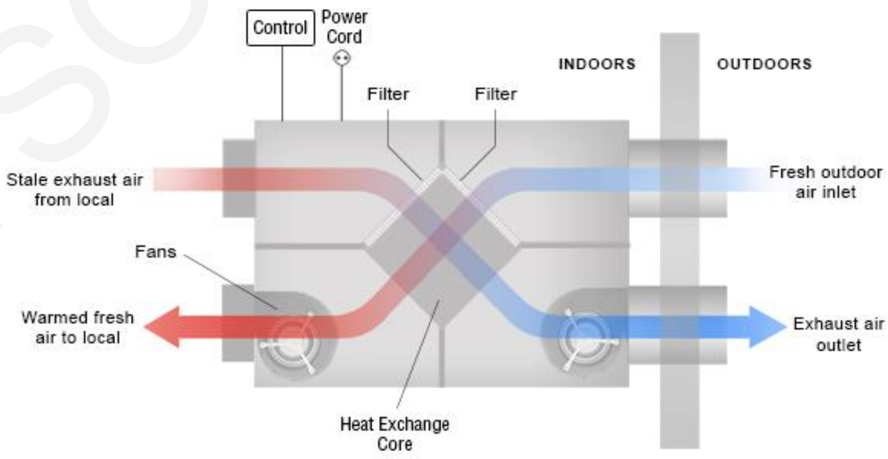



Figure 11.18. Diagram of MVHR system [454].

*11.4.5.5. Combinations*

This section aimed to examine the combinations of afore-mentioned retrofitting scenarios in order to achieve the highest improvement of comfort conditions and energy performance of educational buildings when it is not supported by a technical system. The combinations were created based on the **performance** of individual strategies. Case 23 to Case 26 consider only the improvement of the insulation of the building envelope with different thicknesses of insulation. Night ventilation and a new layer of insulation on the roof are predicted to have the greatest impact on thermal comfort and energy performance, and are considered easy strategies to be applied; therefore, Case 27 examines its effectiveness. Case 28 considers the addition of wall insulation to Case 27. Case 29 and 30 consider construction combinations and window operation; while, Case 31 includes all the passive strategies i.e. the best case of previous scenarios with the addition of movable shading. Case 32 includes the passive strategies of Case 31 with the addition of heat recovery ventilation in order to regulate heat losses during the winter period and ensure decongestion of heat gains of the building envelope during summer period (Table 11.33). Figure 11.19 shows the combinations of construction details.

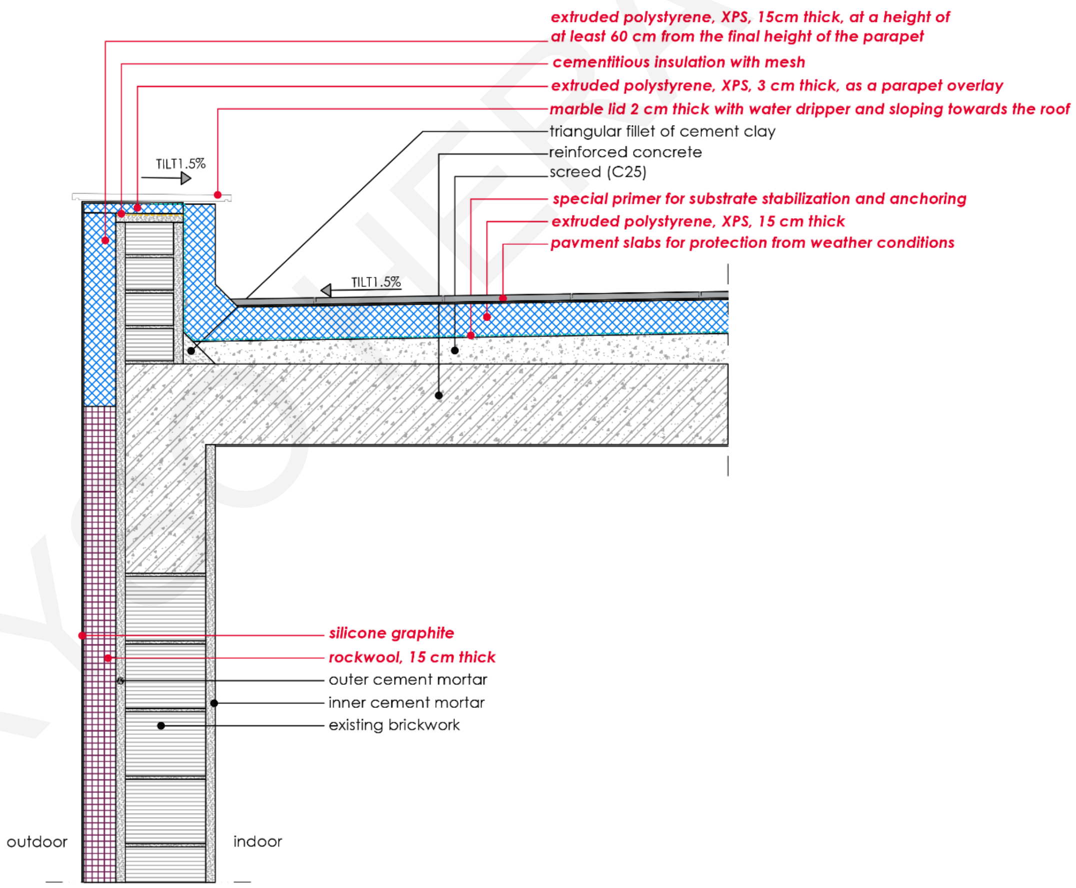



Figure 11.19. Construction detail of wall and roof insulation (Case 26).

Table 11.33. Combinations of scenarios

| Refurbishment strategies | Retrofit option | Refurbishment strategies | Retrofit option |
|---|---|---|---|
| **Combinations** | Construction 1 | C1+C5+C9+C12 | C23 |
| | Construction 2 | C1+C5+C9+C13 | C24 |
| | Construction 3 | C2+C6+C9+C13 | C25 |
| | Construction 4 | C4+C7+C9+C13 | C26 |
| | Roof insulation 15cm + cross vent. during day and night | C7+ C17 | C27 |
| | Roof and wall insulation 15cm + cross ventilation during day and night | C4+C7+C17 | C28 |
| | Construction 3 + window operation | C2+C6+C9+C13+C17 | C29 |
| | Construction 4 + Window operation | C4+C7+C9+C13+C17 | C30 |
| | Construction 4 + Window operation + movable shading | C4+C7+C9+C13+C17+C21 | C31 |
| | Construction 4 + Window operation + movable shading + MVHR | C4+C7+C9+C13+C17+C21+ C22 | C32 |

### *11.4.6. Adaptation measures for energy performance and cost-effectiveness*

For the calculation of the cost effectiveness of adaptation measures, the model that incorporates technical systems is selected. Based on the results of adaptation measures during the first stage (**Chapter 11.4.5**) individual strategies are chosen for the calculation of LCCA while, ten combinations of retrofit scenarios are investigated considering that adaptation measures should satisfy the provision of the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020 onwards, as well as the installation difficulties involved in each scenario. The methodology of the calculation of energy demand and life cycle cost analysis associated with adaptation measures is described in the following chapter, i.e. **Chapter 11.4.7**. For the calculation of the cost effectiveness of adaptation measures, the area of architectural elements and their relevant costs are presented below in order to be considered as part of the life cycle cost analysis. According to the EU guidelines [411], since the macroeconomic perspective has been adopted, the costs have been considered by excluding the VAT.

#### *11.4.6.1. Construction interventions*

All the thermal insulation of the building envelope (wall, roof, floor, windows) described in the previous section (**Chapter 11.4.5.1**) are used for cost effectiveness calculations and are summarized in Table 11.34. It should be mentioned that the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020 onwards, does not accept the insulation of 5cm on the roof and wall as well as double low-e glazing with standard frame; therefore they were excluded from combinations scenarios.

Table 11.34. Retrofitting scenarios for building envelope.

| Refurbishment strategies | | | | | Retrofit option |
|---|---|---|---|---|---|
| **Building envelope properties** | New layer of exterior insulation on the walls | 5 cm | U- value (W/m²K) | 0.43 | C1 |
| | | 8 cm | U- value (W/m²K) | 0.31 | C2 |
| | | 10 cm | U- value (W/m²K) | 0.26 | C3 |
| | | 15 cm | U- value (W/m²K) | 0.18 | C4 |
| | New layer of insulation on the roof | 5 cm | U- value (W/m²K) | 0.53 | C5 |
| | | 10 cm | U- value (W/m²K) | 0.29 | C6 |
| | | 15 cm | U- value (W/m²K) | 0.19 | C7 |
| | | 20 cm | U- value (W/m²K) | 0.15 | C8 |
| | New layer of insulation on the floor | 5 cm | U- value (W/m²K) | 0.5 | C9 |
| | | 8 cm | U- value (W/m²K) | 0.35 | C10 |
| | | 10 cm | U- value (W/m²K) | 0.29 | C11 |
| | Replacement of existing windows with relatively high-performance glazing systems and window frames | double low-e glazing, standard frame | U-value frame (W/m²K) | 5.8 | C12 |
| | | | U-value glaze (W/m²K) | 1.3 | |
| | | | g-value | 0.7 | |
| | | | U-value window (W/m²K) | 3.5 | |
| | | double low-e glazing, insulated frame no.1 | U-value frame (W/m²K) | 4.5 | C13 |
| | | | U-value glaze (W/m²K) | 1.3 | |
| | | | g-value | 0.6 | |
| | | | U-value window (W/m²K) | 2.7 | |
| | | double low-e glazing, insulated frame no.2 | U-value frame (W/m²K) | 2.6 | C14 |
| | | | U-value glaze (W/m²K) | 1.3 | |
| | | | g-value | 0.6 | |
| | | | U-value window (W/m²K) | 2.2 | |
| | | triple glazing, insulated frame | U-value frame (W/m²K) | 2.6 | C15 |
| | | | U-value glaze (W/m²K) | 1 | |
| | | | g-value | 0.5 | |
| | | | U-value window (W/m²K) | 1.3 | |

For the needs of the calculations, Table 11.35 summarizes the area of the building elements for a selected classroom.

Table 11.35. Areas of the architectural elements of the building envelope.

| **Building element** | **Area** |
|---|---|
| **External Walls** | (8.20 x 3) x 2 = 49.2 m² - 16.6 m² (windows) = 32.6 m² |
| **External Roof** | ( 8.20 x 10.25) = 84m² |
| **Internal Floor** | (8 x 7) = 56 m² |
| **Windows** | three-leaf sliding window 2,55 x 1,15 m = 2.93 m²<br>four-leaf sliding window 3.50 x 1,15 m = 4.02 m²<br>opening door, 1 x 2.20 = 2.20 m²<br>three clerestories in a row with the middle only (0.7 x 0.85) operable of total dimensions 2.10 x 0.85= 1.78 m² x 2 = 3.56 m² |

| | |
|---|---|
| | five clerestories in a row with 3 operable areas of total dimensions 3.55 x 0.55 = 1.95$m^2$ x 2= 3.90$m^2$ |

Table 11.36 summarizes the costs associated with the addition of new rockwool render systems on the walls. The cost includes supply and installation.

Table 11.36. Costs related to the installation of a thermal insulation system on the walls.

| Building elements | Cost |
|---|---|
| **Rockwool render system of 5 cm** | € 36/$m^2$ |
| **Rockwool render system of 8 cm** | € 40/$m^2$ |
| **Rockwool ender system of 10 cm** | € 43/$m^2$ |
| **Rockwool render system of 15 cm** | € 48/$m^2$ |
| **Cementitious waterproofing with mesh** | € 18/m2 |
| **Insulation around windows** | € 23/m2 |

Table 11.37 summarizes the cost associated with the installation of a new layer of insulation on the roof. The cost includes supply and installation.

Table 11.37. Costs related to the addition of a new layer of insulation on the roof.

| Building elements | Cost |
|---|---|
| **Special primer** | € 8/$m^2$ |
| **Polystyrene panel of 5 cm** | € 10/$m^2$ |
| **Polystyrene panel of 8 cm** | € 12/$m^2$ |
| **Polystyrene panel of 10 cm** | € 15/$m^2$ |
| **Polystyrene panel of 15 cm** | € 20/$m^2$ |
| **Polystyrene panel of 20 cm** | € 25/$m^2$ |
| **Paving slabs** | € 18/$m^2$ |

Table 11.38 summarizes the cost associated with the addition of a the new layer of insulation on the floor. The cost includes supply and installation.

Table 11.38. Costs related to the new layer of insulation on the floor.

| Building elements | Cost |
|---|---|
| **Polystyrene panel of 5 cm** | € 10/$m^2$ |
| **Polystyrene panel of 8 cm** | € 12/$m^2$ |
| **Polystyrene panel of 10 cm** | € 15/$m^2$ |
| **Screed** | € 13/$m^2$ |
| **Final Floor** | € 45/$m^2$ |

Table 11.39 summarizes the cost associated with the replacement of single-glazed windows with new and improved windows. The cost includes supply and installation.

Table 11.39. Costs related to new window installation.

| Building elements | Cost |
|---|---|
| **Double low-e glazing, standard frame** | €200/m$^2$ |
| **Double low-e glazing, insulated frame no.1** | €250/m$^2$ |
| **Double low-e glazing, insulated frame no.2** | €300/m$^2$ |
| **Triple low-e glazing, insulated frame** | €350/m$^2$ |

*11.4.6.2. Natural ventilation*

As a result of safety reasons associated with the openings of windows during night time, a ventilator that closely imitates the window operation was selected based on the results of the simulation of the first stage. The ventilator that uses its fan for air extraction has an efficiency of 1000 l/s, i.e. 3600m$^3$/h. Case 16 (cross ventilation during daytime) is not taken into consideration for the calculation of LCCA due to very limited impact. The cost of the ventilator is set at 1000€ including installation and supply.

Table 11.40. Retrofitting scenarios for natural ventilation.

| Refurbishment strategies | | | Retrofit option |
|---|---|---|---|
| **Natural ventilation** | Increasing ventilation rate in summer (mid-May to October) | cross ventilation during daytime (07:30-13:30) and night-time (21:00-07:30) | C17 |
| | | cross ventilation only during night-time (21:00-07:30) | C18 |

The cost of a ventilator is summarized in Table 11.41 and includes supply and installation.

Table 11.41. Cost related to extractor fan for assisted natural ventilation.

| Ventilator | Cost |
|---|---|
| **Extractor fan** | 1000 € |

*11.4.6.3. Architectural interventions*

Based on the results of the evaluation of adaptation measures described in the previous section (Chapter 11.4.5.) Case 20 (increase of overhang) was not seletected for calculation of its cost effectiveness due to limited but also negative impact on the performance of educational buildings. Although Case 20 provides negative impact on the thermal and energy performance of the building, it is hereby presented to demonstrate the positive impact during the cooling period.

Table 11.42. Scenarios for architectural interventions.

| Refurbishment strategies | | | Retrofit option |
|---|---|---|---|
| **Geometry** | Shading devices | horizontal louvers 25-5-25-5-25-5<br>solar emissivity: 0.9 | C20 |
| | | external movable horizontal louvers | C21 |

solar emissivity: 0.9
daytime/night-time resistance: 0.1 m$^2$K/W
Transmission factor: 0°=0.65, 15°=0.40, 30°=0.20,
45°=0, 60°=0, 75°=0, 90°=0,
Operation: Winter: 18:00 - 07:00
Summer: 07:00 - 18:00

Table 11.43 summarizes the cost of shading systems per classroom.

Table 11.43. Cost related to shading devices.

| Shading Device | Cost |
|---|---|
| **Fixed shading (3 horizontal aluminium louvers of 0.25m x 8 m)** | € 1250 |
| **Movable shading (3 horizontal aluminium louvers of 0.25m x 8 m) + automation control system** | € 2170 |

*11.4.6.4. Mechanical ventilation system*

A mechanical ventilation system is selected for calculation of its cost-effectiveness. The provision of a mechanical ventilation system with heat recovery maintains indoor air quality and assists heating and cooling needs.

Table 11.44. Scenario for mechanical ventilation.

| Refurbishment strategies | | | Retrofit option |
|---|---|---|---|
| **Mechanical ventilation (MVHR)** | Heat recovery ventilation system (200l/s) | Operation: Winter: 07:30-13:35 on<br>Summer: 07:30-13:35 on,<br>00:00-07:30 and 13:35-24:00<br>on when outdoor air temperature is < 31°C and outdoor relative humidity is <70% | C22 |

Table 11.45 summarizes the cost of individual elements of the MVHR.

Table 11.45. Cost related to MVHR.

| MVHR | Cost |
|---|---|
| Heat recovery unit | €1500 |
| Diffusers | €400 |
| Duct system for filtered air | €1100 |
| Filter material to be exchanged | €100 |
| Metal louver | €500 |
| $CO_2$ sensor | €400 |

*11.4.5.2.5. Combinations*

The combinations of retrofit scenarios are based on the best performance of individual cases in terms of their cost-effectiveness are categorized based on their installation difficulties into light, medium and advance retrofitting. Specifically, light retrofitting involves retrofit options that have high impact to the energy demand and easy installation, thereby avoiding multiple visits and interventions to the users. Medium retrofitting undertakes retrofit options that have high impact to the energy demand and medium difficulties to install while advance retrofitting refers to all the possible retrofit options (including both measures that have high impact and less crucial effect to the energy demand, regardless of construction difficulty) to achieve the greatest reduction in energy demand possible. The difficulty rate is also related to the smooth running of the schools throughout the academic year in terms of maintenance.

Table 11.46. Scenarios for combinations.

| **Refurbishment strategies** | **Retrofit option** | **Description of retrofit option** | **Refurbishment strategies** | **Retrofit option** |
|---|---|---|---|---|
| **Combinations** | Light | Roof ins.10 cm +MVHR | C6 + C22 | C23 |
| | Light | Roof ins.15 cm +MVHR | C7 + C22 | C24 |
| | Light | Roof ins.10 cm +MVHR+ Vent. | C6 + C22 + C17 | C25 |
| | Light | Roof ins.15 cm +MVHR+ Vent. | C7 + C22 + C17 | C26 |
| | Medium | Roof ins.10 cm +MVHR+ Wall ins. 8 cm | C6 + C22 + C2 | C27 |
| | Medium | Roof ins.15 cm +MVHR+ Wall ins. 8 cm | C7 + C22 + C2 | C28 |
| | Medium | Roof ins.10 cm +MVHR+ Wall ins. 10 cm | C6 + C22 + C3 | C29 |
| | Medium | Roof ins.15 cm +MVHR+ Wall ins. 10 cm | C7 + C22 + C3 | C30 |
| | Medium | Roof ins.10 cm +MVHR+ Wall ins. 10 cm+ Vent. | C6 + C22 + C3 + C17 | C31 |
| | Medium | Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Vent. | C7 + C22 + C3 + C17 | C32 |
| | Medium | Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame | C6 + C22 + C3 + C14 | C33 |
| | Medium | Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame | C7 + C22 + C3 + C14 | C34 |
| | Medium | Roof ins.10 cm +MVHR+ Wall ins. 8 cm + Double glazed low-e insulated frame+ Vent | C6 + C22 + C2 + C14 + C17 | C35 |
| | Medium | Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame+ Vent | C6 + C22 + C3 + C14 +C17 | C36 |
| | Medium | Roof ins.15 cm +MVHR+ Wall ins. 8 cm + Double glazed low-e insulated frame+ Vent | C7 + C22 + C2 + C14 + C17 | C37 |

| | | | |
|---|---|---|---|
| Medium | Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame+ Vent | C7 + C22 + C3 + C14 +C17 | C38 |
| Medium | Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame+ Shading | C6 + C22 + C3 + C14 + C21 | C39 |
| Advanced | Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame + Floor ins. 5cm | C6 + C22 + C3 + C14 +C9 | C40 |
| Advanced | Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double-glazed low-e insulated frame + Floor ins. 5cm + Shading + Vent. | C6 + C22 + C3 + C14 + C9 +C21 + C17 | C41 |
| Advanced | Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double-glazed low-e insulated frame + Floor ins. 5cm + Shading + Vent. | C7 + C22 + C3 + C14 + C9 +C21 + C17 | C42 |

### *11.4.7. Data analysis methodology*

For the evaluation of thermal and energy performance of educational buildings in Cyprus and the investigation of the effectiveness of adaptation strategies through software simulation, the data analysis methodology is divided into two parts.

The **first part** considers the evaluation of the thermal and energy performance of the model built for the first and second stage of simulation. First stage of the first part considers the evaluation of educational buildings in their existing state (base case scenario) both in the current and future climatic conditions without any technical systems. The second stage of the first part considers the remodeled version of educational buildings that implements different retrofit scenarios both in the current and future climatic conditions without technical systems.

For the **first part**, the base case scenario and each suggested scenario was carried out using the dynamic software IES-VE, for which the heating and cooling degree hours were calculated for the hours of occupation in the south classrooms for the whole academic year. The final simulation results of the retrofitted educational buildings will be benchmarked against the previous simulation results (before retrofitting) to validate the potential for energy consumption reduction and improvement of thermal comfort conditions.

The **second part** considers the evaluation of energy performance and cost effectiveness of the model built for the third and fourth stage of simulation. The third stage considered the evaluation of educational buildings in their existing state (base case scenario) under the current climatic conditions with the assumption that technical systems are provided to maintain indoor thermal comfort while, the fourth stage considered the remodeled version of educational buildings that implements different retrofit alternatives in the current climatic conditions, with the provision of technical systems.

For the **second part**, the base case and each suggested scenario was carried out using the dynamic software IES-VE, for which the energy consumption in kWh/m$^2$/year was derived from the software and the LCCA was calculated. The final simulation results are of the retrofitted educational buildings and will be benchmarked against the previous simulation results (before retrofitting) to validate the potential for energy consumption reduction and improvement of thermal comfort conditions.

*11.4.7.1. Data analysis methodology for free-running buildings*

Thermal and energy performance data was collected from the Vista Pro and was entered into Microsoft Excel to enable data storage and analysis. Data sets were classified based on specific climatic scenarios. The indoor conditions were assessed based on the environmental data derived from IES-VE. Several indices and mathematical models were used to analyse the indoor comfort conditions and energy performance both in current and future climatic conditions.

*11.4.7.1.1. Adaptive comfort models*

Thermal comfort was assessed using the Adaptive Comfort Standards (ASC), which is incorporated in the EN 15251:2007 [87]. Using the data retrieved from the naturally ventilated buildings, the following relationship was reached when calculating the indoor comfort temperature from the data and using the running mean of the outdoor temperature:

$$T_c\,(°C) = 0.33T_{rm} + 18.8 \qquad \text{(Eq. 11.12)}$$

where, *Tc* is the predicted comfort temperature when the running mean of the outdoor temperature is *Trm*.

Category II [87] that represents the 80% acceptability limit of indoor operative temperatures is suitable for buildings that are refurbished and is calculated with an addition/subtraction of 3°C to Equation (11.12). The adaptive comfort temperatures for different climatic conditions are summarizes below:

- The adaptive comfort temperatures range from 20.6°C to 24.6°C for the lowest temperatures and from the 26.3°C to 30.3°C for the highest temperatures for the 90% acceptability for the TMY;
- The adaptive comfort temperatures range from 19.6°C to 25.6°C for the lowest temperatures and from the 25.3°C to 31.3°C for the highest temperatures for the 80% acceptability for the TMY;
- The adaptive comfort temperatures range from 20.8°C to 24.8°C for the lowest temperatures and from the 26.4°C to 30.4°C for the highest temperatures for the 90% acceptability for the 2050;

- The adaptive comfort temperatures range from 19.8°C to 25.8°C for the lowest temperatures and from the 25.4°C to 31.4°C for the highest temperatures for the 80% acceptability for the 2050;
- The adaptive comfort temperatures range from 21.1°C to 25.1°C for the lowest temperatures and from the 26.8°C to 30.8°C for the highest temperatures for the 90% acceptability for the 2090;
- The adaptive comfort temperatures range from 20.1°C to 26.1°C for the lowest temperatures and from the 25.8°C to 31.8°C for the highest temperatures for the 80% acceptability for the 2090;

Figure 11.20 shows the upper and lower thresholds calculated using Equation (11.12) for Nicosia, Cyprus. The graph highlights the significant range of operative temperatures falling within the acceptable range of comfort depending on the exterior conditions.

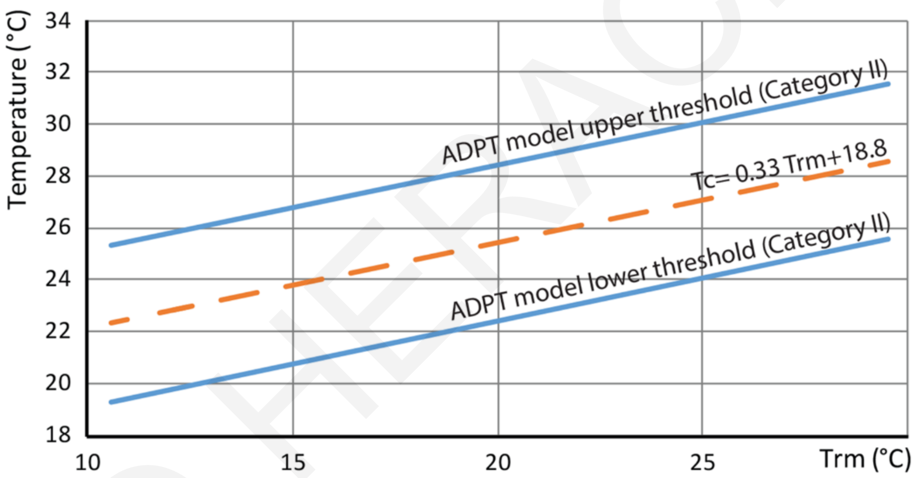



Figure 11.20. Design values for adaptive models of comfort as a function of outdoor temperature running mean [87].

*11.4.7.1.2. Heating and Cooling Degree-Hours*

With regards to the thermal environment, the degree-hours which fall outside of both the higher and lower limit margins can be employed as a performance indicator of building for either the warm or cold seasons. The heating/cooling degree-hours (HDH and CDH) are defined as the sum of the difference between hourly average temperatures and the lower/upper acceptability limit of indoor operative temperature as defined in EN 15251:2007. The value of the heating degree-hours (HDH) in any given day is defined using the Equation (11.13).

$$HDH = \sum_{i=1}^{N}\left(T_{lower\_limit} - To_{average}\right)^{+} \qquad \text{(Eq.11.13)}$$

In the Equation (11.13), N is the number of hours in a day with average hourly operative temperature lower than the lower acceptability limit, $T_{o\_average}$ is the average hourly operative temperature, and

$T_{lower\_limit}$ is the lower acceptability limit to which the degree-hours are calculated. The "+" superscript indicates that only positive values of the bracketed quantity are taken into account in the sum.

Similarly, the cooling degree-hours (CDH) in any given day is defined using the Equation (11.14), where $T_{upper\_limit}$ is the upper acceptability limit to which the degree-hours are calculated:

$$CDH = \sum_{i=1}^{N} \left(To_{average} - T_{upper\_limit}\right)^{+} \quad \text{(Eq.11.14)}$$

*11.4.7.1.3. Overheating criteria*

In this study, overheating was evaluated using the method described in CIBSE TM52, derived from the adaptive comfort EN 15251:2007 (previous version of EN 16798-1:2019). The TM52 analysis method determines a comfort temperature (*Tc*) based on the exponentially weighted running mean external temperature (*Trm*). Moreover, TM52 uses operative temperature, derived from air temperature, mean radiant temperature and air speed, to determine the internal thermal conditions. Finally, according to the CIBSE standards, three criteria were employed to provide a robust, yet balanced, assessment of the overheating risks of buildings during the occupied hours of the cooling period, i.e., from the 1st of May to the 30th of September [455]. The three overheating assessment criteria required by TM52 are presented in detail below:

*Criterion 1: Hours of exceedance (He)*

The first criterion sets a limit for the number of occupied hours that the operative temperature can exceed *Tmax* (Equation (11.15)) during a typical non-heating season (1 May- 30 September). This number shall not exceed 3 per cent of occupied hours [455].

The maximum temperature is 3 °C above comfort temperature levels (from Equation (11.12)) for buildings in free-running mode. Specifically, for such buildings, the maximum acceptable temperature (*Tmax*) is calculated from the running mean of the outdoor temperature (*Trm*) using the formula:

$$Tmax = 0.33Trm + 21.8 \quad \text{(Eq.11.15)}$$

where, *Tmax* is the maximum acceptable temperature (upper threshold).

*Criterion 2: Daily weighted exceedance (We)*

The second criterion deals with the severity of overheating within any single day, which is given in terms of temperature rise and duration and sets a daily acceptability limit.

To allow for the severity of overheating, the weighted exceedance (*We*) shall be less than, or equal to, 6 in any single day where:

$$We = \Sigma\,(he \times wf)$$

$$We = (heo \times 0) + (he1 \times 1) + (he2 \times 2) + (he3 \times 3) \quad \text{(Eq.11.16)}$$

where the weighting factor $wf = 0$ if $\Delta T \leq 0$, otherwise $wf = \Delta T$, and hey is the number of hours when $wf = y$.

*Criterion 3: Upper limit temperature (Tupp)*

To set an absolute maximum value for the indoor operative temperature, the value of ΔT shall not exceed 4 K.

$$Tupp = Tmax + 4 \tag{Eq.11.17}$$

It should be noted that the abovementioned method rates multiple parameters related to the thermal comfort and thus provides a comprehensive evaluation of the overheating risk in naturally ventilated buildings.

The overheating criteria were used only to analyse the overheating risk of educational buildings in the existing state and the upgrade scenario of improved ventilation strategies under current and future climatic conditions.

*11.4.7.2. Data analysis methodology for buildings supported by mechanical systems*

The data from the third and fourth stage was collected from the Vista Pro and was entered into Microsoft Excel, which enable data storage and analysis. Data were classified based on the retrofitting scenario. Several indices and mathematical models were used to analyse the energy performance and life cycle cost of both base case and retrofitting scenarios.

*11.4.7.2.1. Energy evaluation*

The energy efficiency was assessed based on the annual **primary energy consumption** per square meter of the building's air-conditioned area both of the base case as well as for the alternative scenarios derived from IES-VE. Primary energy consumption was selected instead of final energy consumption based on suggestions of the existing energy analysis literature [456], [457] and the fact that this energy form includes the overall efficiency of the energy system, as it takes into account the efficiencies of production, distribution and end-use of an energy source. Therefore, the primary energy consumption values can be directly compared with similar values not only in the same energy system, but also between different energy systems, and express system-wide efficiency performance [458]. The established national primary energy conversion factor of 2.7 and 1.1 for electricity and heating oil in Cyprus respectively, were used to convert the electricity consumption and boiler consumption into primary energy consumption [459]. The national representative conversion emission factor of primary energy of electricity and heating oil is 0.794 and 0.266 of $CO_2$ per kWh, respectively.

*11.4.7.2.2. Economic evaluation*

With respect to the Directive 2010/31/EU and the European Regulation 244/2012/EU [411], a benchmarking mechanism on the basis of cost optimality has been introduced. The framework indicated that investigation of certain economic factors that address the long-term financial status or benefits such as life cycle cost, shall be adopted. In each case, both base case and retrofit scenario are economically compared using the net present value (NPV) method. Life cycle cost represents the cumulative cost expressed in present value over the period of analysis.

The calculation of global cost (or LCCA) requires, for each energy efficiency measure, the initial investment, the sum of the annual costs for every year (including the operational energy costs) and the final value, all with reference to the starting year (2020, for the following case study) of the calculation period. The EU Delegated Regulation defines the global cost for the macroeconomic calculation as in the following equation:

$$C_g(\tau) = c_I + \sum_j \left[\sum_{i=1}^{\tau} (C_{a,i}(j) \times R_d(i) - V_{f,\tau}(j)\right] \quad \text{(Eq. 11.18)}$$

Where

- $\tau$: calculation period;
- $C_g(\tau)$: global cost (referring to the starting year) over the calculation period;
- $C_I$: initial investment costs for the energy efficiency measure or set of measures j;
- $C_{a,i}(j)$: annual cost during the year I for measure or set of measures j (including running costs and replacement costs);
- $V_{f,\tau}(j)$: residual value of measure or set of measures j at the end of the calculation period (discounted to the starting year);
- $R_d(i)$: discount factor of year.

In the following section, the annual costs are the sum of maintenance costs, operational costs, energy cost and replacement cost.

Moreover, the discount factor $R_d$ depends on the real interest rate ($R_r$, %) and on the time of the considered cost. It can be calculated according to Equation (11.19), where $p$ is the number of years from the starting period.

$$R_d(i) = \left(\frac{1}{1+R_r}\right)^p \quad \text{(Eq. 11.19)}$$

According to the European Standard EN 15459-1:2017, the calculation period of the global energy performance associated cost was set to 30 years with the study referring to public buildings.

Table 11.47 summarizes the lifespan of building components as considered in the following analysis, and the annual preventive maintenance cost including operation, inspection, cleaning, adjustments, repairs and consumable items as percentage factor (Mc) of the initial investment cost.

Table 11.47. Lifespan of building components and annual maintenance, operation, repair and service factor of system components.

| Component | Lifespan (p) – in years | Mc (%) | Reference |
|---|---|---|---|
| **Wall finishes of thermal facade** | 15 | 0 | Local market |
| **Windows** | 30 | 1 | Local market |
| **Insulation** | 50 | 4 | Ascione et al. [460], Loukaidou et al. [429] |
| **Roofing- membrane** | 20 | 1 | Wang and Holmberg [425] |
| **Roofing-tile** | 80 | 0 | Wang and Holmberg [425] |
| **MVHR** | 20 | 0.4 | EN 15459-1:2017 [412], |
| Filter material to be exchanged | 1 | 0 | Local market |
| **Extractor fan** | 20 | 4 | EN 15459-1:2017 [412] |
| **External shutter fixed** | 30 | 4 | Local market |
| **External shutter automated** | 30 | 6 | Local market |
| Electronics | 20 | | |

Additional maintenance cost was added annually for supervision and cleaning of the roof at 1% of the initial cost (i.e. 40€/year), and for rubbing and varnishing of the floor at 2% of the initial cost (i.e. €50/year or €500/10years).

It should be noted that for the reference building, the windows, wall and roof maintenance is differentiated considering its particular characteristics and age. Specifically, wall maintenance was set to 6€/m$^2$ for refreshing the wall rendering every five years and roof maintenance was set to 11€/m$^2$ for renewal of the roof membrane every 20 years. Windows maintenance includes lubrication of mechanisms with silicone spray and lubrication of sealing tires and that represent the 2% of the initial cost (€100/year).

The other economic parameters used for the global cost calculation are shown in Table 11.48, according to the European indication [412] and the guidelines of the Building Performance Institute Europe [461].

Heating oil and electricity tariffs for the starting year come from the Retail Fuel Prices Observatory and Cyprus Energy Regulatory Authority and these include regional and national taxes. The percentage of change of the electricity price as shown in the last 5 years, was observed with an average of 2.2% and was included for the future estimation of the price. The reduction of the electricity price due to the pandemic was neglected, as it is assumed that the energy price will rise again at the end of pandemic. The percentage of increase of the heating oil price worldwide was observed for the last 10 years with an average of 3.8% which was included for the future estimation of the price.

The period of calculations for public buildings according to the European Regulation 244/2012/EU [411], has an impact on the residual values of various building elements at the end of the observation period. Over a 30 year calculation period, replacement costs are considered only for technical installations.

The residual value can be determined by means of a straight-line depreciation of the initial investment costs of the building element, until the end of the calculation period and therefore discounted at the beginning of the calculation period. The residual value is considered only for the paving slabs and technical systems with a depreciation factor of 10 % respectively, regarding the cost of materials.

Table 11.48. Economic parameters for the evaluation of the global cost.

| | | |
|---|---|---|
| **Calculation period (T)** | 30 years | EN 15459-1:2017 [412] |
| **Real interest rate ($R_r$)** | 0 | Bloomberg Markets |
| **Discount rate (Rd)** | 0.28 (10 years) | Bloomberg Markets |
| | 0.55 (15 years) | Bloomberg Markets |
| | 0.84 (20 years) | Bloomberg Markets |
| | 0.90 (25 years) | Bloomberg Markets |
| | 1.08 (30 years) | Bloomberg Markets |
| **Electricity cost** | 0.1689 / $kWh_e$<br>2.20% increase per year | Cyprus Energy Regulatory Authority |
| **Heating oil cost** | 0.069/ kWht<br>3.8% increase per year | Retail Fuel Prices Observatory |

*11.4.7.2.2. Sensitivity analysis*

Sensitivity analysis is very useful to determine the impact of the value of a particular variable, especially if it differs from the expected one. The robustness of the key parameters such as the evolution of energy prices and discount rates can be evaluated. The sensitivity analysis aims to be useful for decision making or development of recommendations of decision makers, communication, increased understanding or quantification of the system and the development of a model. The selection of a cost-optimal refurbishment solution belongs to the early stage decision-making. The economic analysis is subject to future variables that might fluctuate and a sensitivity analysis is helpful for making decisions or providing recommendations. This analysis allows to evaluate how the optimal solution is robust, under what circumstances it would change and in which way. For this study, a sensitivity analysis for different discount rates and energy prices for heating oil and electricity will be considered.

At the moment, there is low inflation and interest rate. Thus, both the cost of capital and the required rate of return of investments have been falling in the general economy. In many countries, a discount rate of 3% (in real terms) is often used for the calculations of the feasibility of energy efficiency projects in existing and new buildings. It is also the suggested value by the normative framework [411]. Therefore, the first case of sensitivity analysis examines a discount rate of 3% throughout the whole calculation period.

Regarding the evolution of the energy price, an additional increase of 0.5% in the rate of increase per year is considered as a future projection for both electricity and heating oil prices (i.e. 2.7% increase of electricity and 4.3% increase of heating oil) for the first case. The second case examines a small decrease of 0.5% in the rate of increase of the energy price (i.e. increase of 1.7% of electricity and increase of 3.3% of heating oil).

Lastly, due to the trend towards all-day use of schools for other activities, the sensitivity of the life cycle cost of the adaptation measures is investigated in order to find out if these measures help more in the utilization of school structures and how they affect their life cycle. For that reason, the technical systems during the afternoon between 14:45 and 17:45 was activated.

## 11.5. Chapter Summary

This chapter described in detail the research methods applied to the objective, i.e. field measurements and dynamic simulation and subjective, i.e. questionnaires, approaches employed in this study. The case study has been introduced and detailed information has been provided. The instrumentation to collect indoor and outdoor climate data and the measurement procedure were deployed in line with the recommendations of the widely used standards. The data methodology, to assess the existing state and upgraded educational building using different ventilation strategies on-site, was described. Additionally, information was provided for the questionnaires designed specifically for students in naturally ventilated classrooms in order to cover their subjective opinion about indoor comfort conditions. Finally, in order to assess the levels of thermal comfort and energy performance vulnerability of schools in Cyprus and the effectiveness of passive strategies both in the current and future climatic conditions, the methodology using dynamic software simulation was thoroughly explained. The case study building has been modelled and calibrated using dynamic simulation software (IES-VE), in order to determine the potential impact of climate change (2050, 2090) under the A1B scenario. Future scenarios show that the air temperature will rise both during winter and summer, with an average annual increase of 0.7°C in 2050 and 1.7°C in 2090. The highest increase appears during the spring period with an average increase of 1.2°C and 2.3°C in April for 2050 and 2090 respectively. Additionally, the mean minimum temperature will rise by about 1.5°C and 3°C for 2050 and 2090 respectively, leading to hotter nights. Regarding the retrofitting approaches, the methodology for the calculation of cost-effectiveness was provided using the life cycle cost analysis.

The process of synthesizing the results, objective in the case of scientific approaches (recording, computational methods, software simulation) and subjective in the case of anthropocentric (questionnaires, field observation), ensure the most complete, in terms of comfort, approach to the school building.

# Chapter 12. Methodology to assess the indoor air quality in correlation with thermal comfort in educational buildings and proposed measures for improved air quality under current climatic conditions

## 12.1. Introduction

This chapter presents the methods employed to assess indoor air quality in correlation with thermal comfort of existing educational buildings and proposes measures for improved air quality under current climatic conditions. In this study, the experimental approach was performed in the same case study building. Fieldwork procedures during cool and warm conditions of the local school year combined the measurement of physical variables of the classrooms with a survey of students' subjective responses, using questionnaires specifically designed for the target age group. Specifically, various ventilation strategies and window opening patterns were examined, in order to identify the best option to exploit natural ventilation as a means to achieve optimum air quality, especially during wintertime. The in-situ measurements of temperature and relative humidity were analysed in correlation with $CO_2$ levels. Additionally, quantitative study through structured field observation monitored occupant behaviour and the manual control of windows. This chapter first presents details of the environmental monitoring equipment and the measurement procedure; as well as the data analysis methodology. The methods used for the administration of the air quality survey are described.

## 12.2. Quantitative study through field measurements and observation

The accomplishment of research in schools received granting permission form the Ministry of Education and Culture, Secondary General Education (Appendix A); while the accomplishment of research in the Archbishop Makarios III Secondary School received granting permission from the School District office of Aglantzia (Appendix B). The characteristics of the case study building are described in **Chapter 10.7.**

### *12.2.1. Environmental data collection procedure and instrumentation*

A field study was carried out for the investigation of air quality, thermal comfort and the impact of natural ventilation based on the above parameters in educational buildings, during the cold winter period, specifically from 10$^{th}$ February to 16$^{th}$ February 2018. This particular period was selected because it represents the coldest period of the year. A more detailed investigation was performed a few days later, between the 3$^{rd}$ and 9$^{th}$ March 2018. The investigation also took place during the warm period, from 19th May to 25th May 2018. The data was collected during both occupied and unoccupied periods. Air temperature, globe temperature, air speed, relative humidity, and $CO_2$ concentration were measured. Details regarding instrument specification and accuracy, position of equipment in the classroom and data retrieval are presented in **Chapter 11.2.1**. Figure 12.1 shows the plan layout and position of equipment in selected classrooms.

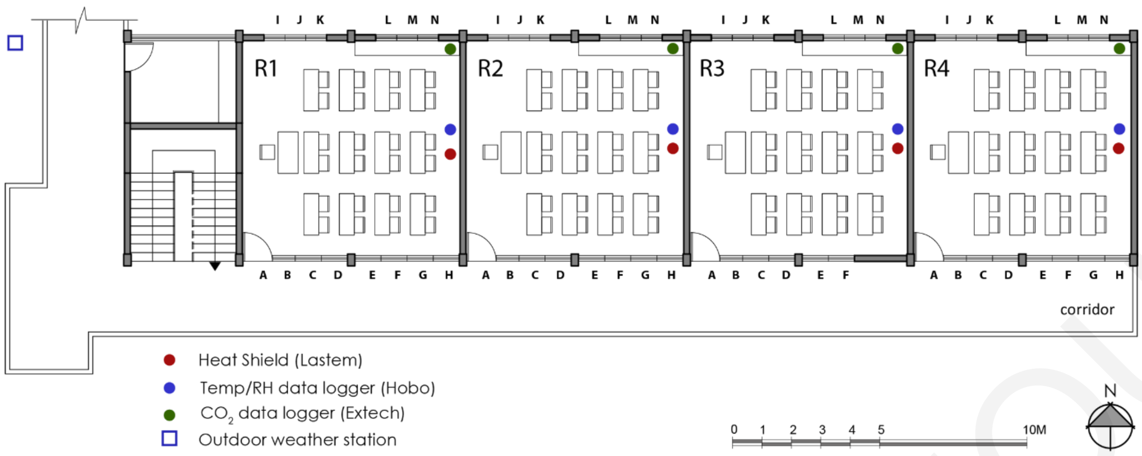



Figure 12.1. Plan layout of a typical classroom of secondary schools in Cyprus where the openings A to N, and the locations of the installed recording equipment, for indoor and outdoor environmental conditions are indicated.

In this framework, free-pattern ventilation strategies as well as different experimental ventilation strategies were examined in order to identify the behaviour of educational buildings and determine possible improvements. The objective of the experiments was to achieve optimum air quality with the least adverse impact on thermal comfort. The experiment was conducted in two periods in winter, following some observations made in the first period (Table 12.1) and one period in the summer (Table 12.2.). The data was monitored for both occupied and unoccupied hours. Specifically, the different experimental ventilation strategies were examined between Saturday and Tuesday (inclusively), while the free pattern of openings was monitored between Wednesday and Friday.

### *12.2.2. Monitoring of occupant behaviour regarding the manual control of windows through filed observation and assessment of indoor air quality*

For each seasonal period, the behaviour of occupants vis-à-vis window manual control in educational buildings was monitored for three days of the week in the four classrooms. The monitoring indented to trace the relationship between the daily activity of the occupants and window control patterns so as to quantify the impact environmental variables have on the window-opening (and closing) behaviour of occupants. Moreover, the monitoring assessed the IAQ of classrooms under the in-use scenario and the effectiveness of different window patterns. Window opening as a ventilation strategy does not only benefit the indoor environment but also improves thermal comfort.

### *12.2.3. Proposed experimental scenarios using different ventilation strategies for the improvement of air quality in correlation with thermal comfort*

In the first experimental monitoring period, single sided ventilation strategies were examined for different time of the day in four classrooms. The openings that remained fully opened were C and F (that is half of openable windows in single sided). In Case 4, windows opened during all break times (08:50-09:10, 10:30-10:50 and 12:10-12:15), in Case 3, windows opened in the last two breaks, in Case 2, windows opened during the last break only in midday. In Case 1, all the openings remained closed, i.e., no ventilation was monitored, to be used as a reference scenario.

During the second experimental monitoring period, attention was paid to different opening patterns of Case 4 (i.e., openings remained open during all break-times). In case 7, the same opening pattern was used as Case 4, i.e., openings C and F remained fully open during break-time. In Case 5, all openable windows of a single side remained fully open (i.e., C, E, and G), and in Case 6, cross ventilation was achieved when openings C, F, J and M remained fully open during break-time. In Case 8, opening C and F remained fully open together with door A; however, door A also remained fully open during teaching periods in order to provide continuous fresh air. The ventilation strategies, investigated during the field study, are summarized in Table 12.1.

During the third experimental monitoring period, the objective was to indicate the most effective cooling strategy; thus, both single-sided and cross-ventilation strategies were employed for different times of the day in the four south facing classrooms. Specifically, the different ventilation strategies were examined for four consecutive days, i.e. during the weekend, and on Monday and Tuesday. Specifically, single-sided ventilation and cross-ventilation was proposed during the daytime, and cross-ventilation was proposed during the daytime as well as during the night time, and night time alone. In Case 1, single-sided daytime ventilation occurs in the morning hours, i.e. 07:00-13:30 with openings A, C, and F remaining fully open. For comparison reasons, in Case 4, cross-ventilation also occurs in the morning hours, i.e. 07:00-13:30 with openings A, C, F, J and M remaining fully open. In Case 2, cross-ventilation was proposed for both daytime and nigh time, i.e. 07:00-13:30 and 21:00-07:00 with openings A, C, F, J and M remaining fully open. In Case 3, the classroom remained closed during the teaching hours to reduce heat gains; however, the door (i.e. opening A) remained open throughout the day to maintain indoor air quality. Cross-ventilation is proposed during the night, i.e. 21:00-07:00, to reduce the extensive heat stored in the building envelope. It is noted that in all cases under study that employed night ventilation, the door of the classroom remained closed for safety reasons.

Table 12.1. Ventilation strategies and window opening patterns examined during the field study period. Dots indicate open windows during specific time-periods of the day.

| **Case / Classroom** | | **Ventilation strategies Openings remained open** | | | **Break time** | | | **Teaching period** | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | **1st break** 20 mins | **2nd break** 20 mins | **3rd break** 5 mins | **Full day ventilation** 7:30-13:35 | **Openings remained open** |
| **First experimental monitoring period** | | | | | | | | | |
| **Case 1** | R1 | - | - | | - | - | - | - | - |
| **Case 2** | R2 | Single Sided 1 | C, F | 1.75 $m^2$ | - | - | ■ | - | - |
| **Case 3** | R3 | Single Sided 1 | C, F | 1.75 $m^2$ | - | ■ | ■ | - | - |
| **Case 4** | R4 | Single Sided 1 | C, F | 1.75 $m^2$ | ■ | ■ | ■ | - | - |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Second experimental monitoring period** | | | | | | | | | |
| **Case 5** | R1 | Single Sided 2 | C, E, G | 2.63 $m^2$ | ■ | ■ | ■ | - | - |
| **Case 6** | R2 | Cross | C, F, J, M | 4.75 $m^2$ | ■ | ■ | ■ | - | - |
| **Case 7** | R3 | Single Sided 1 | C, F | 1.75 $m^2$ | ■ | ■ | ■ | - | - |
| **Case 8** | R4 | Single Sided 1 & Door | A, C, F | 3.65 $m^2$ | ■ | ■ | ■ | ■ | A |

Table 12.2. Ventilation strategies and window opening patterns examined during the field summer period. Dots indicate open windows during the specific time of the day.

| **Third experimental monitoring period** | | | | | |
|---|---|---|---|---|---|
| **Case** | Ventilation strategies | Window opening patterns | | | |
| | | Openings remained open | | Operation | |
| **SUMMER PERIOD** | | | | | |
| | | Window name | Total Size ($m^2$) | Day (07:00-13:35) | Night (21:00-07:00) |
| **Case 1 (R1)** | Single-sided | A, C, F | 3.65 | ■ | - |
| **Case 2 (R2)** | Cross | A, C, F, J, M | 4.75 | ■ | ■ |
| **Case 3 (R3)** | Cross | A, C, F, J, M | 4.75 | - | ■ |
| **Case 4 (R4)** | Cross | A, C, F, J, M | 4.75 | ■ | - |

### *12.2.4. Data analysis methodology*

The $CO_2$ concentration was analysed in correlation with the air temperature of both the internal and external environment in order to assess indoor air quality and thermal comfort, the contribution of each ventilation strategy to air quality and thermal comfort. According to the Representatives of European Heating and Ventilation Associations (REHVA), the acceptable limit for $CO_2$ levels is 1500 ppm [231]. The same limit is set by the authority of the public educational buildings in the United Kingdom [232], and the same appears in the German and Swiss Standards [462], [463]. According to the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) standards [220], the limiting value during the occupied period is 700 ppm above outdoor $CO_2$ levels (300-500 ppm). According to the European Standard EN 13779:2007 [229], maximum indoor air quality is achieved with less than 400ppm above outdoor levels, medium quality is achieved when $CO_2$ levels is 400-600ppm above the level of outdoor levels, moderate quality when $CO_2$ levels is from 600 to 1000 ppm  above the outdoor level and low quality when $CO_2$ levels is above 1000 ppm of outdoor air level. In this research, the $CO_2$ concentration of 1500 ppm was set as an acceptable limit.

The thermal comfort was assessed using the adaptive comfort standard used in naturally ventilated buildings where occupants have different expectations, compared to those who stay in technically supported buildings, due to their adaptation to the external environment incorporated in EN 15251:2007. The equations are analysed in **Chapter 11.2.3**.

## 12.3. Qualitative survey through questionnaires

### *12.3.1. Methodology for conducting field research using questionnaires*

The study considered thermal comfort and indoor air quality qualitative survey through questionnaires to gather data for the assessment of comfort conditions. This approach sought to capture the subjective point of view of students, introducing parameters related to biological, emotional and psychological data of students. The procedure for conducting field research and the structure and design of the research tool are described extensively in **Chapter 11.3**.

Specifically, the fourth section of the questionnaire dealt with air quality and humidity and included questions concerning perception and preferences including dryness, freshness, odour, movement and overall air quality performance. The aim was the comparative presentation of these data sets, with the quantitative (objective) data of recording; and analysis and the drawing of relevant conclusions.

Questionnaires were filled in by n=317 secondary school students during the school year 2017-2018. The survey was conducted during the winter period, from the $15^{th}$ of January to $17^{th}$ of January 2018, and by n=289 students during the summer period, from $09^{th}$ of May to $11^{th}$ of May 2018. Students' age ranged from 12 to 15 years old. Out of the total number of participants, 50% were boys and the other 50% were girls. The questionnaires were filled in by students while sitting in their classrooms during the teaching periods.

For this study, five-point Likert scale questions were included in the questionnaire in order to assess the students' perceptions of indoor air quality, in a representative classroom, in a typical educational building in Cyprus. Table 12.3 summaries the scale of questionnaire for the air quality survey.

Table 12.3. Scales of questionnaires for the air quality survey.

| Parameter | Scale | | | | |
|---|---|---|---|---|---|
| **Dryness/dampness** | -2 | -1 | **0** | 1 | 2 |
| | dry | | **neutral** | | moist |
| **Freshness** | **1** | 2 | 3 | 4 | 5 |
| | **fresh** | | | | heavy |
| **Odour** | **1** | 2 | 3 | 4 | 5 |
| | **odourless** | | | | smells strongly |
| **Air movement** | -2 | -1 | **0** | 1 | 2 |
| | Still | | **neutral** | | With many currents |
| **Air quality performance** | **1** | 2 | 3 | 4 | 5 |
| | **very satisfactory** | | | | not satisfactory |

*Note: The ideal condition is indicated by bold*

### *12.3.2. Data analysis methodology*

Data from students' subjective responses to the questionnaire were coded and imported to a spreadsheet. The data were analysed using statistical analysis methods used in other air quality comfort studies. The analysis was performed using Microsoft Excel. The characterization of air quality indices was described based on the mean, standard deviation and range in the form of a percentage.

## 12.4. Chapter summary

This chapter described in detail the research methods applied to assess indoor air quality under current climatic conditions. More specifically, the study describes the methodology in order to trace the correlation between the daily activity of occupants and the window control pattern, investigating the conditions of appropriate manual airing. In this framework, various ventilation strategies and window opening patterns were examined in order to identify suitable practices to achieve optimum air quality without negatively affecting the thermal comfort of indoor spaces. The in-situ measurements of $CO_2$ levels were analysed in correlation with temperature and relative humidity. Additionally, qualitative survey was conducted using questionnaires in order to gather users' views on air quality conditions.

# Chapter 13. Methodology to assess the lighting performance and visual comfort of educational buildings and proposed measures for improved lighting performance under current climatic conditions

## 13.1. Introduction

This chapter investigates the natural lighting performance of typical educational school premises in Cyprus and propose solutions to improve visual comfort in classrooms. Natural lighting is an important factor in the design of education buildings as it creates a pleasant environment, it promotes healthier conditions and ensures energy saving. For the purposes of the present research, an in-depth lighting performance analysis was carried out in a typical classroom in Cyprus. Firstly, this section describes the methodology for the validation of the simulation using field measurements. Additionally, the methodology for a field study carried out through a questionnaire-based survey is described. The evaluation of the lighting performance and visual comfort in educational buildings in Cyprus was performed through static and dynamic validated simulations which are also described in detail together with the lighting performance criteria. Finally, potential improvements are proposed in order to achieve better visual comfort in typical educational school premises in Cyprus and in other areas of southern Europe with similar climatic characteristics and typologies in educational architecture.

## 13.2. Quantitative study through field measurements for validation purposes

The short distance among the climatic zones of Cyprus and the fairly similar latitude and longitude allow the investigation of natural lighting in only one climatic zone. The case study is the same school used for the analysis of the thermal comfort and indoor air quality of educational buildings.

Four typical classrooms of general education, one in each orientation, were selected for in-depth analysis. Openings along the two long sides of the space (i.e. extensive windows towards the interior side and clerestories towards the exterior) provide daylighting into the classroom indoor space. The openings to floor ratio is 35%. It should be noted that openings are not directly shaded by any building or plant elements. Windows have single 4 mm thick clear float glass, with light transmittance of 0.90, within aluminium frames of 60 mm width. The aluminium frame to window ratio is 15%. The direct connection of classrooms with semi-open corridors ensures an external overhang of 2 m to all windows, allowing the management of solar radiation, as well as the regulation of natural lighting. The clerestories in the other long side of the classroom have no external shading control. It is noted that all openings of the typical classroom, both windows and clerestories, have internal black-out curtains that allow shading control by users. More information about the case study are shown in **Chapter 10.7.**

Field measurements of natural lighting were employed in order to verify the software simulation; therefore, a validation process was conducted so that the simulation results would match the levels and distribution of the in-situ measured illuminance levels. Natural lighting measurements were conducted on-site in classrooms during summer solstice, i.e. June 21st under conditions of mostly clear sky (2/8) and during winter solstice, i.e. December 21st under an intermediate sky (4/8) at 09.00 am and 12.00 noon (local time GMT+2). Sky conditions tended to be the representative ones for each period as shown in Table 13.1. The equipment TECPEL 536 Light Meter RS232 Data Logger was employed. Lighting data were taken from specific points of the classroom, in a grid of 1 m in both directions, which coincides with the centre of the grid at the openings of the classroom. The lighting data was taken at a height of 0.75 m from the classroom's finished floor level, i.e. the level of the desk's working surface. During monitoring, the classroom was free from users, artificial lighting was not used and curtains were wide open. During the in-situ measurement, acknowledged guidelines on methods and appropriate techniques for effective and accurate repeatable in-situ measurements were taken into account [464].

Table 13.1. Percentage frequencies of clear, intermediate and cloudy skies for Nicosia, lowland region CZ2, Meteonorm software.

| **Location** | **Sky Condition** | **Cloud Coverage** | **Winter (%)** | **Spring (%)** | **Summer (%)** | **Autumn (%)** |
|---|---|---|---|---|---|---|
| **Nicosia Lowland Region CZ2** | Clear | 0/8 | 0 | 0 | 0 | 0 |
| | Mostly clear | 2/8 | 0 | 7 | **51** | 3 |
| | Intermediate | 4/8 | **76** | **78** | **48** | **78** |
| | Mostly Cloudy | 6/8 | 24 | 15 | 0 | 19 |
| | Cloudy | 8/8 | 0 | 0 | 0 | 0 |

## 13.3. Qualitative survey through questionnaires

### *13.3.1. Methodology for conducting field research using questionnaires*

For the better understanding of visual comfort conditions in the indoor space of the typical classroom, a questionnaire-based survey was carried out, involving a large number of building-users, i.e. students and teachers, in the school. A comprehensive questionnaire was developed as a methodological tool, suitable to collect all the information needed to address the purpose and goals of the specific study (Appendix E). The use of a questionnaire is the most widely used data collection method in qualitative research [465]. In order to reduce measurement errors and to establish validity and reliability of the results, the development of questionnaires was based on international recognized practices [466], [467]. For the evaluation of visual comfort conditions in the typical classroom of the education buildings in Cyprus, seven-point Likert scale questions were used. Respondents were asked to respond to a

Questionnaires were distributed to a random sample of n=400 students, n=190 boys (47.5%) and n=210 girls (52.5%) participated in the study. Of the total number of students:

- 26.0% of the participants were first grade students (aged 13);
- 44.0% were second grade students (aged 14); and,
- 30.0% were third grade students (aged 15).

The same questionnaire, with minor alternations, was distributed to a sample of teachers. Specifically, n=19 men (41.3%) and n=27 women (58.7%), of all specializations and with teaching experience between 3 to 31 years, responded to the questionnaire.

The questionnaire includes a series of questions which aim to evaluate the characteristics of the classroom, i.e. the floor level and the orientation of the respondent's classroom, and to determine the respondent's position within the classroom, i.e. distance of the respondent's desk from the nearest window and clerestory. A series of questions concerned the evaluation of daylighting levels and visual comfort of the respondents. Specifically, the questions refer to the evaluation of daylight in terms of (i) brightness or darkness, (ii) lighting uniformity, (iii) glare issues, and (iv) overall evaluation of natural lighting levels. Finally, the respondents were asked to indicate the periods of year and times of day that artificial lighting is used. For the analysis of the questionnaire-based survey results, graphical representations were prepared.

For this study, seven-point Likert scale questions were included in the questionnaire in order to assess the visual comfort in a representative classroom in a typical educational building in Cyprus. Table 13.2 summaries the scale of questionnaire for the visual comfort survey.

Table 13.2. Scales of questionnaires for the natural lighting survey

| **Parameter** | | | | **Scale** | | | |
|---|---|---|---|---|---|---|---|
| **Brightness/Darkness** | 1 | 2 | 3 | **4** | 5 | 6 | 7 |
| | Very dark | | | **Neutral** | | | Very bright |
| **Lighting Uniformity** | **1** | 2 | 3 | 4 | 5 | 6 | 7 |
| | **Uniform** | | | | | | Non-uniform |
| **Glare Issues** | **1** | 2 | 3 | 4 | 5 | 6 | 7 |
| | **No glare** | | | | | | Glare |
| **Natural Lighting Performance** | **1** | 2 | 3 | 4 | 5 | 6 | 7 |
| | **Very satisfactory** | | | | | | Not satisfactory |

*Note: The ideal condition is indicated by bold*

### *13.3.2. Data analysis methodology*

Data from students' subjective responses to the questionnaire were coded and imported to that spreadsheet. The analyses were performed using Microsoft Excel. The characterization of visual comfort indices is presented in the form of a percentage.

## 13.4. Lighting simulation for the evaluation of natural lighting performance and proposed improvements

### *13.4.1. Software*

For the evaluation of the lighting performance of educational buildings, software simulation was employed. Several computer-aided software tools were used to integrate daylighting in the building analysis. For the purposes of the present study, Autodesk Ecotect Analysis 2011 [468], Desktop Radiance v.2.0 [469], Beta Daysim v.3.1 [470] and Hdrscope [471] were selected. Autodesk Ecotect Analysis 2011 was used as a modelling and visualization tool. Daylight simulation was performed using Desktop Radiance and Daysim, which produce more accurate results for daylight analysis than other software. More specifically, the Radiance software is able to examine advanced lighting regimes using the backward ray-tracing technique and is considered as one of the most powerful and popular among lighting simulation software [472], [473]. It has also been validated to predict appropriate internal illuminance by a high degree of accuracy and it has special daylight simulation capacity, such as a number of specular reflectors and materials, as well as use of a sophisticated sky model i.e. CIE standard sky [474]–[476]. Daysim software is a dynamic radiance-based daylight simulation tool. Its algorithm, based on the daylight coefficient method, and the Perez Sky Model, is able to calculate annual illumination levels. Daysim software also incorporates the Evalglare which is suitable for glare analysis. For the evaluation of glare, the present study employed the Hdrscope software to post-process HDR images that originate from HDR photographs and Radiance Lighting Simulation and Visualization program. This software provides a user-friendly and integrated medium for this purpose [477].

### *13.4.2. Modeling and validation*

The 3D model was drawn up taking into account the geometry of the classroom in a way that the digital representation would approach the real building with the highest level of accuracy. The geometrical simulation of a typical classroom was performed according to the dimensions of the interior space and was reproduced in order to create the linear disposition of three classrooms. Special attention was paid to the representation of the building openings. Specifically, the walls were extruded by 0.30 m to obtain the actual construction thickness, while the aluminium frames of windows were designed and extruded based on the geometry of the window frames. Single-glazed windows were used for calculation. A linear corridor in contact with the classrooms and an overhang of 2.00 m in width were included in the simulation model. Other natural lighting control systems, e.g. internal curtains, were not taken into consideration in the natural lighting simulation (Figure 13.1).

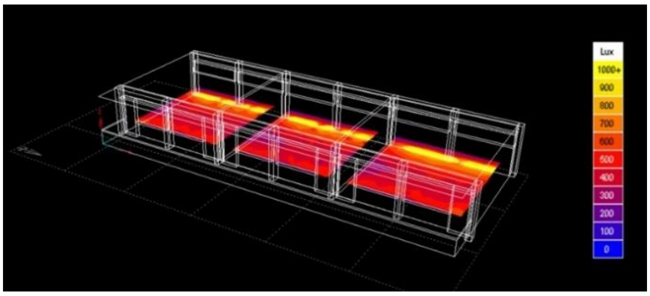



Figure 13.1. The three-dimensional digital model of typical classrooms of educational buildings in Autodesk Ecotect Analysis 2011.

The reflectance values of the on-site materials were conducted according to literature references, using materials' files from Desktop Radiance software. The reflectivity of interior surfaces was determined based on the IESNA Lighting Handbook [298], at 0.60 for plaster wall finishes painted with light yellowish ochre colour, 0.85 for the plaster ceiling finishes painted with white colour and 0.20 for the floor finishes made of greyish coloured matt mosaics tiles.

The sky model was set as clear for the 21$^{th}$ of June and as intermediate for 21$^{st}$ of December, based on the sky conditions during the in-situ lighting measurements (CIE Illumination Standards). As to the climatic data, the reference standard year of Nicosia was used. The calculations were made using three indirect reflections, employing an analysis grid at 0.75 m height from the finished floor level.

In order to verify the software simulation, a validation process was conducted via Desktop Radiance. The validation process was conducted for classrooms in all four orientations during different periods of the year and hours of the days, i.e. June 21$^{st}$ and December 21$^{st}$, at 9:00 a.m. and 12:00 noon. The results conducted via Desktop Radiance were then introduced in Ecotect software in order to create isolux contours diagrams. These diagrams allowed the evaluation of the correlation between in-situ illuminance measurements and simulated illuminance values. For illustration purposes, the validation of the east-oriented classroom is shown in Figure 13.2. As shown, the results show the good predicted quality of the model. Some variations might be occurred due to the time needed to take the on-site recordings while the simulation captures the natural lighting levels at one specific moment.

In order to obtain simulation results as closer to the values and the distribution of in-situ measured illumination levels as possible, the model received by author all the necessary corrections of geometry and internal surfaces' reflective factors. The repetition of this process ensures adequate correlation between in-situ and simulated illuminance values for classrooms in all four orientations and for all aforementioned days and hours. However, it should be noted that a perfect match between in-situ and simulated illuminance values is difficult due to the simultaneous/parallel validation process of numerous cases. The most important parameters which contribute to the minor differentiations, presented in both the lighting levels and distribution between the in-situ measurements and simulation model, concern the applied techniques of the in situ-measurements, i.e. difference of less than 5$^{o}$ in the orientation of the classrooms, as well as the time period required for the data recording of classrooms under study, in contrast to the time specific results of the simulation process.

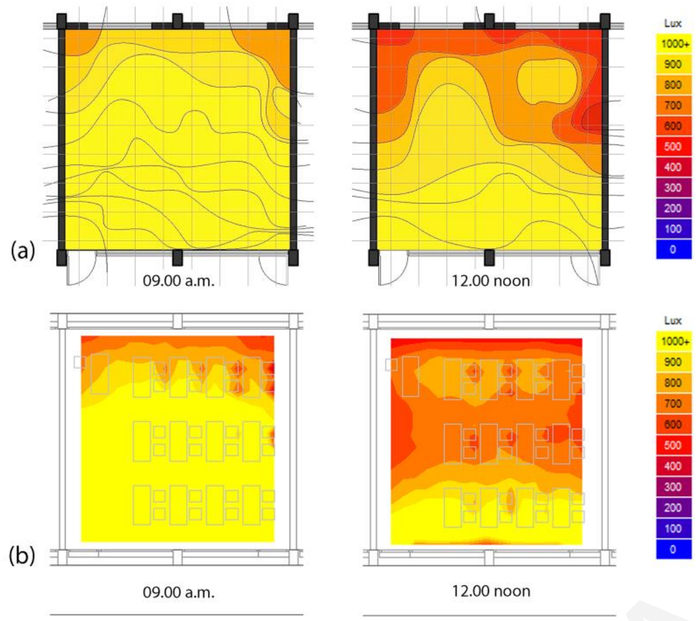



Figure 13.2. Correlation between (a) in-situ illuminance measurements and (b) simulated illuminance values on June 21st, at 9:00 a.m. and 12:00 noon, for east orientated classrooms, after the validation process.

### *13.4.3. Proposed measures for visual comfort improvements*

Louvers and blinds are systems designed to prevent concentrations of sunlight in the building interior closest to the (building) envelope. Moreover, a substantial amount of research has shown that the integration of louvers or blinds systems may lead to substantial energy savings [478]–[480]. Depending on their geometry and shape, louvers and blinds have the ability to redirect sunlight towards the back of a space, thus improving the lighting distribution of the interior [481]. Rotation angle, shape, size, configuration and colour of slats are features that impact on the effective transmittance, reflectance and absorption of shading systems, and thus influence their effectiveness as shading and lighting regulating systems [482], [483]. Light shelves also protect the areas near the glazing from direct solar radiation, while they improve the visual comfort in the interior space due to better lighting distribution as well as to the reduction of glare issues. However, it should be pointed out that light shelves are only effective when light falls directly onto them [484]. Due to the existing overhang in front of large windows of the typical classroom, light shelves are not deemed as a feasible solution for the improvement of visual comfort in the spaces under study.

The investigation of the lighting performance of classrooms led to improvements, which were implemented in the selected classroom in all four orientations using simulation software. The proposed measures concerned the provision of shading, which should not limit daylighting levels and visual comfort. The proposed solutions include (a) the integration of an external shading device, i.e. fixed louvers, and (b) integration of an external shading device combined with an internal movable semi-transparent fabric so as to reduce glare issues without significant reduction of daylighting levels.

The reference scenario, i.e. the typical classroom in its existing status, and the proposed improvement solutions for each orientation, were analysed using climate-based daylight modeling, in order to evaluate the lighting performance for the entire year.

### *13.4.4. Data analysis methodology*

#### *13.4.4.1. Static daylight performance metrics*

The required lighting level in a space depends on the kind of work, duration and time of work (day or night), the building-users' age, etc. The regulations and standards of lighting in educational buildings have differed over the years [281]. According to the current regulations and specifically the CIBSE Guide A [296], [297] and IESNA [24], the minimum illuminance on the working plane for classrooms should be 300 lux. Another static indicator of daylight performance is the DF i.e. daylight factor. This is the most widely used index which defines the ratio of interior illuminance on a horizontal surface to the exterior illuminance on a horizontal surface under an overcast (CIE) sky. According to BREEAM standards [300], the minimum DF should be at least 2% for 80% of the space and according to CIBSE [296], [297] this should be at least 2% for 75% of the space.

Apart from daylighting requirements, the uniformity daylight ratio should also be met in order to achieve successful daylighting. Light uniformity describes how evenly light is spread over a task area. Moreover, high uniformity of light contributes to avoiding visual stress and thus to reduction of the risk for visual discomfort [301]. According to BREEAM, a uniformity ratio, i.e. minimum DF / average DF, of at least 0.4 or a minimum point daylight factor of at least 0.8% is required for sufficient daylighting. However, according to the Department for Education and Employment of the UK [302], uniformity ratio of at least 0.3 is accepted for side-lit spaces.

#### *13.4.4.2. Dynamic daylight performance metric*

According to the study of Reinhardt, Mardaljevic and Rogers [303], dynamic daylight performance metrics are based on timed series of illuminances in buildings which take into consideration the entire year, the quantity and character of daily and seasonal variations of daylight for a given building, as well as irregular meteorological events. Such indicators are i) Daylight Autonomy (DA), defined as the percentage of the occupied hours of the year when a minimum illuminance threshold is met only by daylight, (ii) Useful Daylight Illuminances (UDI), which represents the percentage of time in which the daylight level is useful for the occupants and is divided into three intervals, i.e. too dark (<100 lux), useful daylight (100-2000 lux) and too bright with the possibility of glare issues and discomfort (>2000 lux), and (iii) Maximum Daylight Autonomy (DAmax) which is defined as a sliding level equal to ten times the design illuminance of a space. DAmax is often used as the percentage of a workplane in which the maximum accepted illuminance is exceeded for more than 5% of the occupied hours of the year. The minimum illuminance required for the buildings under study is 300 lux. Following the climate-based simulation and the daylight autonomy (DA), a space that receives sufficient daylight (>300 lux), at least half of the occupied hours of the year, is considered a well day-lit space [304].

*13.4.4.3. Analysis of glare metric*

Excessive daylight is undesirable and may cause glare issues. Glare is a measure of the physical discomfort of an occupant caused by excessive light or contrast in a specific field. It is dependent on the luminance distribution in the observer's field of view [305]. Glare is typically categorized as either disability glare or discomfort glare [306]. Disability glare is defined as a sensation of annoyance caused by high or non-uniform distributions of brightness in the field of view and it may be caused either directly from the luminous source or through reflections [305]. Discomfort glare is defined as the irritating or even painful sensation that can be evoked from a bright visible light source in the field of view. Most glare-related indices or metrics aim at evaluating discomfort glare and are computed with equations that correlate luminance values to human glare sensation [298]. According to Andersen et al. [307], a credible prediction of glare using indices still poses significant challenges in the building as: (i) it depends on the observer's position, (ii) tolerance to glare varies depending on the individual, his/her background, his/her capability to adapt to the light environment, and (iii) the range of assessed luminance can be very wide. According to Carlucci et al. [301], the most appropriate metric to analyse absolute glare issues is the Discomfort Glare Probability (DGP) as it shows a stronger correlation with the user's response in terms of glare perception [308]. DGP is a short-term, local, one-tailed index assessing discomfort glare which is defined as shown in equation (13.1):

$$DGP = 5.87 \cdot 10^{-5}\, \mathrm{E}_V + 0.0918 \cdot \log 10 \left[1 + \sum_{i=1}^{n} \left(\frac{L_{s,i}^2 \cdot \omega_{s,i}}{E_V^{1.87} \cdot P_i^2}\right)\right] + 0.16 \qquad \text{(Eq.13.1)}$$

where $E_v$ is the vertical eye illuminance, produced by the light source [lux]; $L_S$ the luminance of the source [cd/m$^2$]; $\omega_s$ the solid angle of the source seen by an observer; $P$ is the position index, which expresses the change in experienced discomfort glare relative to the angular displacement of the source (azimuth and elevation) from the observer's line of sight. The equation is valid within the range of DGP between 0.2 and 0.8 and for vertical eye illuminance ($E_v$) above 380 lux. Specifically, the degrees of glare sensation are as follows: imperceptible (< 0.30), perceptible (0.30-0.35), disturbing (0.35-0.40), and intolerable (> 0.45).

## 13.5. Chapter summary

This chapter described in detail the research methods applied to assessed the natural daylighting performance of the typical classroom, in all orientations of educational buildings in Cyprus, under the current climatic conditions. The investigation of illuminance and visual comfort, by the simultaneous use of different methodological tools, informed a holistic approach to the study, which leads to a qualitative and systematic quantitative evaluation process that safeguards the reliability of the research results. Specifically, in-situ lighting measurements allowed the evaluation of natural daylighting performance of education buildings through primary research data. Moreover, it enabled the validation of the digital simulation model used for static, dynamic and glare analysis. Visual comfort was studied through the assessment of recognised metrics in terms of the amount of light, the uniformity of light, and the prediction of the risk of both discomfort and disability glare for occupants. In addition to the quantitative research outlined above, a field-based questionnaire survey was used to provide a better understanding of lighting levels, lighting distribution, visual comfort conditions and use of artificial lighting within the classroom.

# PART C. RESULTS AND DISCUSSION

Part C provides an assessment of the environmental comfort conditions and energy performance of a typical Cypriot school building. In this instance, evaluation of environmental comfort conditions refers specifically to the evaluation of thermal comfort, visual comfort, and air quality of the classrooms of a typical school building. Additionally, this part provides the evaluation of the impact of proposed improvements. The evaluation is based on the case-by-case investigation methodologies followed, namely on the analysis of recording data through recording equipment, on the results of the simulation using software and on the results of the field research using questionnaires.

# Chapter 14. Assessment of the thermal comfort and energy performance of educational buildings under current and future climatic scenarios, Part A: Existing state

## 14.1. Introduction

This chapter is organized into three main subdivisions to present the analysis of evaluation of thermal comfort and energy performance of existing educational buildings under current and future climatic conditions for the warm and cool seasons. The first section of this chapter describes the results from the field measurements of environmental variables for each season; the second reports the results of the subjective approach through questionnaires and, the third section describes the results of the dynamic simulation under different climatic conditions and the life cycle cost analysis of the existing buildings, and concludes with a synopsis and discussion.

## 14.2. Results of field measurements

The evaluation of the results of recording environmental variables is divided in two phases. The **first phase of measurements** was carried out at Archbishop Makarios III Secondary School in Nicosia from December 2017 to August 2018 in order to cover all seasons, in classrooms with different orientation and floors and works as a preliminary analysis in order to identify the periods and classrooms where thorough investigation is needed. The evaluation of thermal comfort is based on the comparative evaluation of temperature and humidity data between different orientations for the three recording periods. The **second phase of measurements** focused on selected periods for in depth investigation and took place in the southern classrooms. The recorded data refers to air temperature, globe temperature, air velocity, relative humidity and $CO_2$ concertation. The methodology of the quantitative study through field measurements was described in **Chapter 11.2.**

### *14.2.1. First series of measurements recording temperature and relative humidity*

The monitoring was done almost for a full calendar year, from December 2017 to August 2018. For the annual recording, the thermal behaviour of school buildings is analyzed for three periods as follows:

- 10th February -16th February 2018 (winter)
- 31st March - 06th April 2018 (intermediate)
- 19th May - 25th May 2018 (summer)

The evaluation of thermal performance of classrooms of educational building is made using graphical representation, which allow the comparative evaluation and outcome of conclusions. For each seasonal period comparison was made: (a) in classrooms with different orientations and same roof exposure ((1) south- USB 21, east-USB 33, north-USB 36, west-USB 24, (2) USB 47 and USB 49), (b) in classrooms with same orientations and different roof exposure (south: USB 21 and USB 47 and east: USB 33 and USB 49) and (c) in classrooms with the same orientation but different structure in terms of sun protection (south USB 21, USB 47, USB 37) (Figure.11.1. and Figure 11.2)

The analysis was made during the occupied periods (07:30-13:35), for the whole day (00:00-24:00) and during the weekends where no technical system is provided. It is noted that some classrooms were also used in the afternoon (14:45-18:00) with a smaller number of occupants, i.e., 6-8 in each classroom. As already mentioned, the openings of the classrooms appear on both long sides of the classroom (**Chapter 10.7**). The characterization of the classrooms in terms of orientation is by the direction of the main openings.

*14.2.1.1. Period of recording and analysis of thermal behaviour from 10th of February to 16th of February 2018*

In the following graphical representations (Figure 14.1), the mean maximum, minimum, average, standard deviation and fluctuation values of temperature and relative humidity is presented in each orientation with same roof exposure for the whole week and weekend throughout the day (00:00-24:00). Fluctuation is defined as the difference between maximum to minimum temperature.

It should be noted that technical heating during winter is available through a central heating system with hot water radiators and diesel heated boilers between 07:00-10:00 every weekday and 14:45-17:45 on Monday, Tuesday, Thursday and Friday. Moreover, classrooms in west and north orientation had additional air conditioning, controlled by the teacher. This had significant impact on the recordings both in temperature and relative humidity therefore the analysis of weekends was also made.

The mean maximum outdoor temperature during the week is 18°C. The highest mean maximum temperature during the week throughout the whole day analysis is exhibited in the west-oriented classroom with value 24.0 °C, i.e. 3.1 °C higher from the lowest maximum temperature appeared in the east orientation with value 20.9 °C. The mean maximum temperature of north and south-oriented classrooms is at 22.3 °C and 21.5 °C. The high temperatures in west and north orientation is attributed to the existence of additional air-conditioning in these classrooms. Moreover, the north-oriented classroom has its south clerestories unshaded and the west-oriented classroom has its west clerestories unshaded allowing heat gains. The mean minimum outdoor temperature during week is

10.1 °C. Respectively, the highest minimum temperature during week throughout the whole day analysis is exhibited in the west-oriented classroom with value 19.9 °C, followed by the north-oriented classroom with value 18.8 °C and the south-oriented classroom with value 18.3 °C. The lowest minimum temperature during the week is apparent in the east-oriented classroom with value 18.1 °C. During the week, the mean indoor temperature fluctuation ranges from 2.8 to 4.1 °C, while the mean outdoor temperature fluctuation is 7.9°C.

The mean maximum outdoor temperature during the weekend is 18.6°C. The highest mean maximum temperature during the weekend throughout the whole day analysis is exhibited again in the west-oriented classroom with value 21.4 °C, i.e. 1.5 °C higher from the lowest maximum temperature appeared in the east orientation with value 19.9 °C. The mean maximum temperature of north and south-oriented classrooms is at 20.3 °C and 20 °C. The high temperatures in west and north orientation are affected from the existence of additional air-conditioning in these classrooms during the weekdays and the unshaded windows. The mean minimum outdoor temperature during the weekend is 12.3 °C. Respectively, the highest minimum temperature during the weekend throughout the whole day analysis is exhibited in the west-oriented classroom with value 20.1°C, followed by the north-oriented classroom with value 19.2 °C and the south-oriented classroom with value 18.9 °C. The lowest minimum temperature during the weekend is apparent in the east-oriented classroom with value 18.7 °C. During the weekend, the mean indoor temperature fluctuation is lower compared to weekdays due to the absence of a technical heating system and ranges from 1.1 to 1.2 °C while, the mean outdoor temperature fluctuation is 6.3°C.

The mean maximum outdoor relative humidity during the week is 86.1%. The highest mean maximum relative humidity during the week throughout the whole day analysis is exhibited in the south-oriented classroom with value 61.1%, i.e. 12.6% higher from the lowest maximum relative humidity evident in the west orientation with value 48.5%. The mean maximum relative humidity of north and east-oriented classrooms is at 57.8% and 58.5%. The mean minimum outdoor relative humidity during the week is 56.9%. The highest minimum relative humidity during the week throughout the whole day analysis is exhibited in the south-oriented classroom with value 48.0%, followed by the north-oriented classroom with value 46.7% and the east-oriented classroom with value 45.0%. The lowest minimum relative humidity during the week is evident in the west-oriented classroom with value 41.7% due to the usage of air-conditioning. During the week, the mean indoor relative humidity fluctuation ranges from 6.8% to 13.5%, while the mean outdoor relative humidity fluctuation is 29.3%.

The mean maximum outdoor relative humidity during the weekend is 89.5%. The highest mean maximum relative humidity during the weekend throughout the whole day analysis is exhibited in the east-oriented classroom with value 68.1%, i.e. 16.2% higher from the lowest maximum relative humidity evident in the west orientation with value 51.9%. The mean maximum relative humidity of the north and south-oriented classrooms is at 61.1% and 61.5%. The mean minimum outdoor relative humidity during the weekend is 71%. The highest minimum relative humidity during the weekend throughout the whole day analysis is exhibited in the north-oriented classroom with value 58.7%, followed by the south-oriented classroom with value 55.9% and the east-oriented classroom with value 53.8%. The lowest minimum relative humidity during the weekend is evident in the west-oriented classroom with value 49.0% due to higher temperatures. During the weekend, the mean indoor relative humidity fluctuation ranges from 2.4% to 14.3%, while the mean outdoor relative humidity fluctuation is 18.5%.


Figure 14.1. Comparative evaluation of mean temperature and relative humidity of classrooms throughout the whole week and weekend, during the entire day for the period of recording: 9th of February to 16th of February, 2018.

From the Figure 14.2 and Figure 14.3, which show the temperature and relative humidity distribution of classrooms with same roof exposure (to the outside environment) in different orientations, several conclusions can be derived for the change of values within 24hours.

The highest mean temperature values during occupied the period appear in the west-oriented classroom due to the existence of air conditioning, during both the entire week and weekend. During the weekend, the mean average value of air temperature of the west-oriented classroom is 20.5 °C, while the second highest mean average air temperature appears in the south orientation with value 19.6 °C. The north-oriented classroom has a mean average value of 19.5°C and the east-oriented classroom has a value of 19.3°C. The maximum temperature is exhibited at approximately 12:00-13:00. During the week, the highest mean temperature appears mostly at 10:00 in all classrooms due to the increase of the external temperature and the provision of heating by a technical system switched off at 10:00, with the temperature dropping down until it is switched on again at 14:45 when it begins to rise. The lowest mean minimum temperature appears in all orientations at around 08:00-08:30.

During the weekday, the minimum temperature appears at 07:00, the time before the heating system starts to operate. As a result of heating by a technical system, the temperature fluctuation during the occupied time of weekdays is higher (i.e. ranges from 1.8 to 2.6 °C) compared to the weekend which ranges between 0.2 and 0.6 °C.

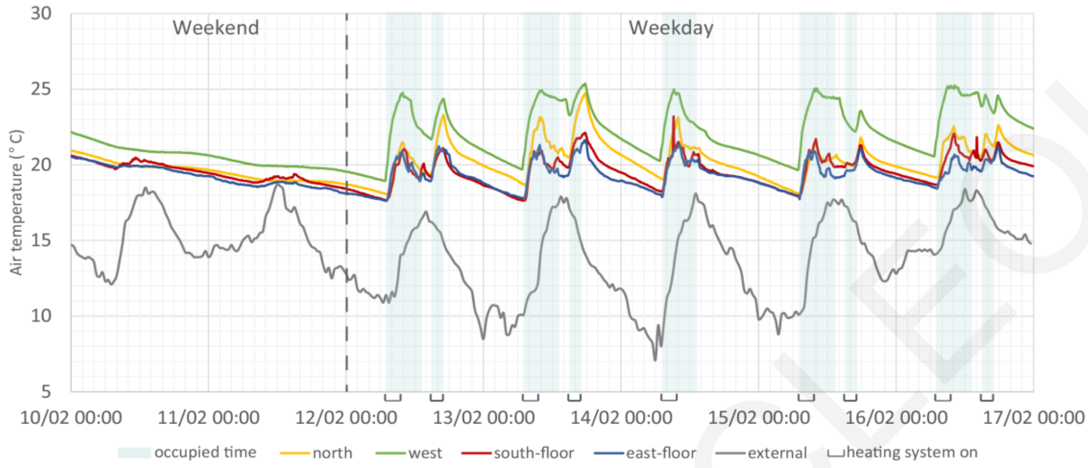



Figure 14.2. Temperature distribution of classrooms with same roof exposure in different orientations from the 10th of February to the 16th of February, 2018.

The highest mean relative humidity values during occupied period are exhibited in the south-oriented classroom during the entire week, while during the weekend it is in the east-oriented. During the weekend, the mean average value of relative humidity of the east-oriented classroom is 62.8%, while the second highest mean average relative humidity appears in the north orientation with value 59.1%. The south-oriented classroom has a mean average value of 58.3% and the west-oriented classroom has a value of 50.2%. The maximum and minimum values of relative humidity vary in terms time of appearance throughout the entire week and therefore it is difficult to derive a conclusion regarding this aspect. What is undoubtedly observed it that the occupants and the heating system affect the results in a great extent.

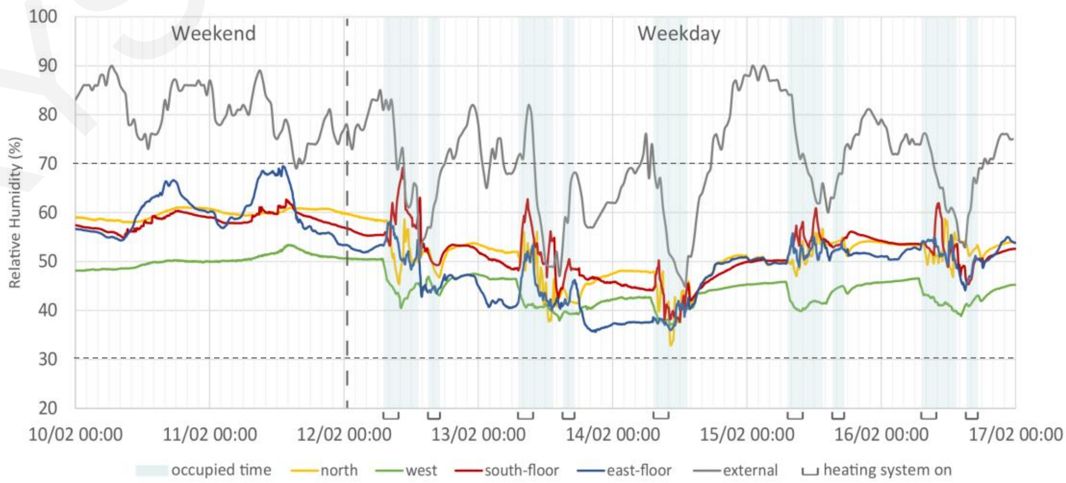



Figure 14.3. Relative humidity distribution of classrooms with same roof exposure, in different orientations from the 10th of February to the 16th of February, 2018. Dashed line indicates the acceptable limits.

Figure 14.4 shows various comparative evaluations of air temperature in classrooms during the winter period. Specifically, comparisons are made between (a) classrooms with same orientation and different roof exposure, (b) classrooms with the same orientation but different design features in terms of sun protection, and (c) classrooms with different orientation and same roof exposure.

In Figure 14.4 (a), the comparison is made between classrooms in east orientation with different roof exposure, i.e. one is located on the ground floor covered by the classroom on the first floor and the second is located on the first floor having its roof exposed to the external environment. As shown, the east-oriented classroom on the ground floor has slightly higher temperatures compared to the classroom on the first floor. As the sun is located at a low altitude in the east orientation, it affects in a similar way the classrooms during the morning, with the classroom on the ground floor showing higher temperatures during the day as it is protected from heat losses through the roof. The mean average temperature during the occupied period of the entire week is 20.1°C in the ground floor, while it is 19.8°C in the first floor.

In a similar context, a south-oriented classroom of the ground floor is compared with a south-oriented classroom on the first floor in Figure 13.4 b. As shown, the south-oriented classroom on the ground floor has significantly higher temperatures compared to the classroom on the first floor, with a difference of the mean values during occupied period of 1.7°C. Specifically, the mean average temperatures during the occupied period are 21.8°C and 20.1°C on the ground and first floor classrooms respectively. This is also attributed to the fact that the ground floor is protected from heat losses through the roof.

In Figure 14.4.b a comparison is also made between classrooms with the same orientation and roof exposure but different design features in terms of sun protection. Specifically, comparison is made between the classroom in the south orientation of the first floor and the classroom located on the ground floor with its roof exposed to the external environment and a horizontal louver of 0.50m depth as a shading system of south openings and an overhang of 2.00 m located on the north side. The classroom with the additional design elements shows the lowest mean temperatures during the recording period with a temperature of 19.7 °C.

Finally, in Figure 14.4.c comparison is made between classrooms with same roof exposure and different orientation, i.e. a south-oriented classroom on the ground floor and an east-oriented classroom on the ground floor. As shown, the south-oriented classroom performs better than the east-oriented classroom on the ground floor. This is attributed to the fact that south-oriented classrooms receive higher solar radiation than east-oriented classrooms. Specifically, the mean average temperature of the south-oriented classroom is 1.7°C higher than the east-oriented classroom during the occupied time with a value of 21.8°C, compared to the 20.1°C of the east-oriented classroom.

Figure 14.5 shows the relative humidity distribution of the abovementioned comparisons. The relationship between temperature and relative humidity is inversely proportional and it is clearer during the weekend when there are no heating systems and occupants in the classrooms.

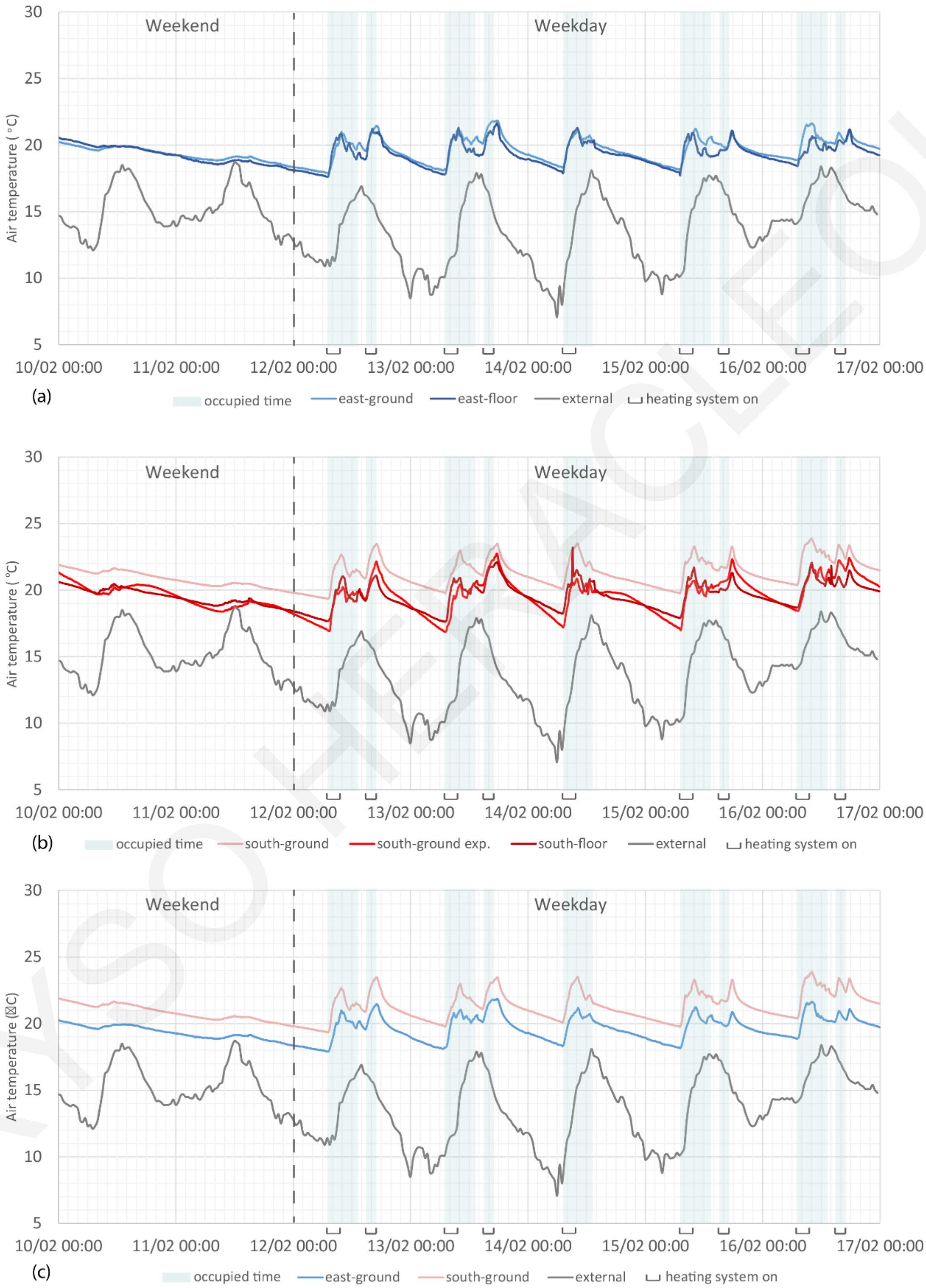



Figure 14.4. Comparison of air temperature between (a) classrooms with same orientations and different roof exposure (east), (bi) classrooms with same orientations and different roof exposure (south) and (bii) classrooms with the same orientation (south) but different structure in terms of sun protection, and (c) in classrooms with different orientations (east and south) and same roof exposure orientations, from the 10th of February to the 16th of February, 2018.

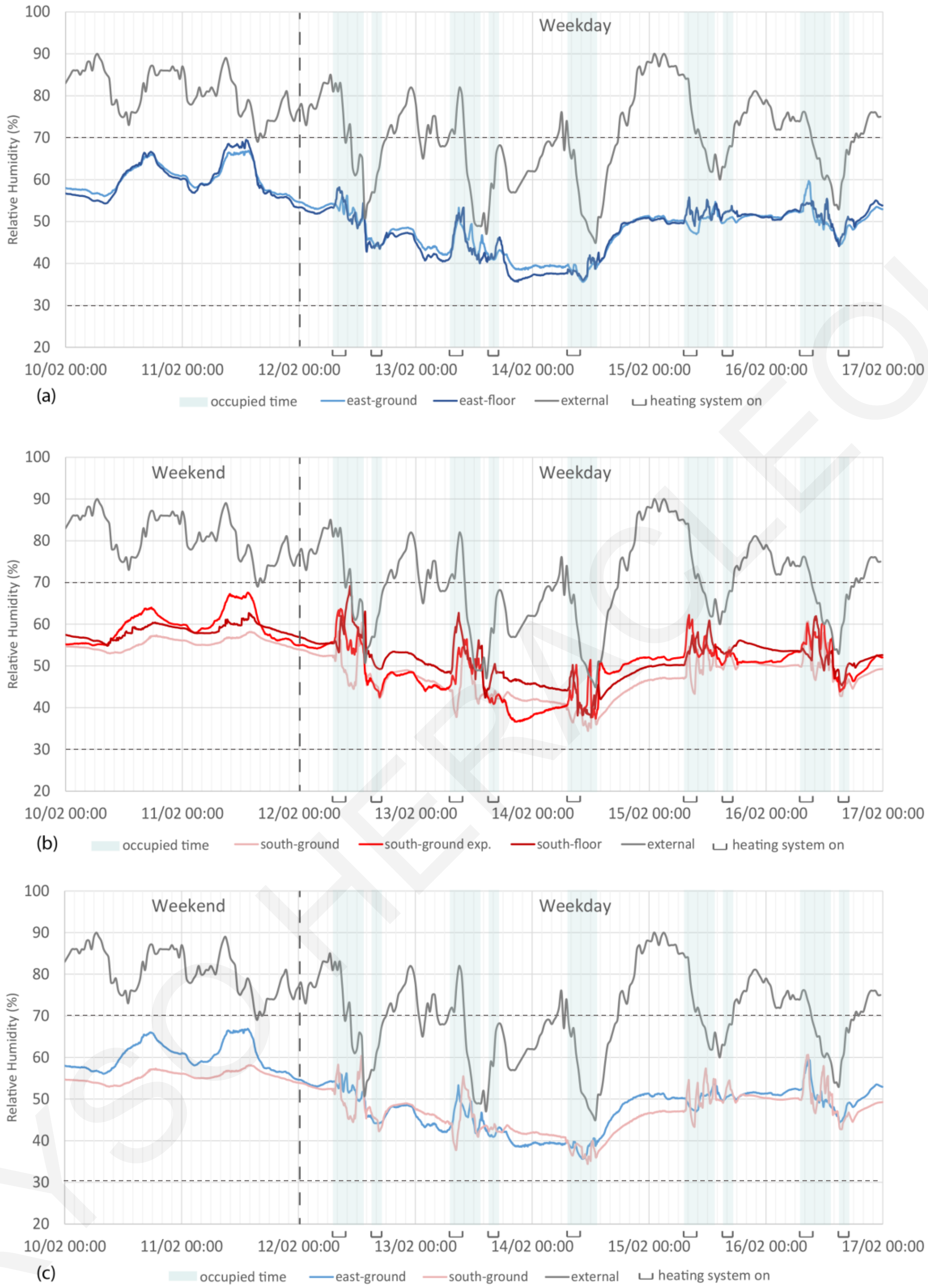



Figure 14.5. Comparison of air temperature between (a) classrooms with same orientations and different roof exposure (east), (bi) classrooms with same orientations and different roof exposure (south) and (bii) classrooms with the same orientation (south) but different structure in terms of sun protection, and (c) in classrooms with different orientations (east and south) and same roof exposure orientations from the 10th of February to the 16th of February, 2018. Dashed line indicates the acceptable limits.

Table 14.1 and Table 14.2 summarized the recorded mean values of air temperature and relative humidity respectively in all selected classrooms during the occupied period (07:30-13:35) both for the whole week and weekend from 10th February to 16th February 2018. Table 13.3 and Table 14.4 summarized the recorded mean values of air temperature and relative humidity respectively in all selected classrooms throughout the entire day (00:00-24:00) for both the whole week and weekend from 10th February to 16th February 2018.

Table 14.1. Recorded mean values of air temperature in all selected classrooms during the occupied period (07:30-13:35) for the weekdays and weekend from the 10th of February to the 16th of February, 2018.

| **Temp.** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, occupied time** | max | 20.7 | 22.7 | 20.5 | 21.6 | 23.7 | 21.2 | 20.6 | 18.0 |
| | min | 18.8 | 20.4 | 18.0 | 18.9 | 21.6 | 18.6 | 18.8 | 11.9 |
| | mean | 20.1 | 21.8 | 19.7 | 20.5 | 23.0 | 20.1 | 19.8 | 15.5 |
| | st. dev. | 0.5 | 0.5 | 0.6 | 0.6 | 0.6 | 0.5 | 0.4 | 2.1 |
| | fluct. | 2.0 | 2.2 | 2.5 | 2.7 | 2.2 | 2.6 | 1.8 | 6.1 |
| **Weekend, occupied time** | max | 19.5 | 21.1 | 19.5 | 19.6 | 20.6 | 19.9 | 19.4 | 18.6 |
| | min | 19.2 | 20.8 | 19.0 | 19.4 | 20.4 | 19.3 | 19.2 | 13.6 |
| | mean | 19.4 | 20.9 | 19.2 | 19.5 | 20.5 | 19.6 | 19.3 | 16.5 |
| | st. dev. | 0.1 | 0.1 | 0.2 | 0.1 | 0.1 | 0.2 | 0.1 | 1.8 |
| | fluct. | 0.3 | 0.3 | 0.5 | 0.3 | 0.3 | 0.6 | 0.2 | 5.0 |

Table 14.2. Recorded mean values of relative humidity in all selected classrooms during the occupied period (07:30-13:35) both for the weekdays and weekend from the 10th of February to the 16th of February, 2018.

| **RH** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, occupied time** | max | 56.2 | 55.2 | 60.4 | 56.8 | 45.9 | 60.6 | 56.8 | 81.4 |
| | min | 48.4 | 45.0 | 50.2 | 46.7 | 42.2 | 50.2 | 48.2 | 59.0 |
| | mean | 51.9 | 49.6 | 55.2 | 51.7 | 43.8 | 54.7 | 52.5 | 69.5 |
| | st. dev. | 2.2 | 2.8 | 2.8 | 2.7 | 0.9 | 2.7 | 2.5 | 7.7 |
| | fluct. | 7.8 | 10.2 | 10.3 | 10.0 | 3.7 | 10.5 | 8.6 | 22.4 |
| **Weekend, occupied time** | max | 64.6 | 56.1 | 64.5 | 59.8 | 51.5 | 59.8 | 66.1 | 88.5 |
| | min | 58.5 | 54.3 | 58.1 | 58.7 | 49.5 | 56.6 | 58.1 | 74.0 |
| | mean | 62.1 | 55.1 | 61.8 | 59.1 | 50.2 | 58.3 | 62.8 | 80.5 |
| | st. dev. | 1.9 | 0.5 | 2.0 | 0.3 | 0.5 | 0.9 | 2.4 | 4.9 |
| | fluct. | 6.1 | 1.9 | 6.4 | 1.1 | 2.0 | 3.3 | 8.0 | 14.5 |

Table 14.3. Recorded mean values of air temperature respectively in all selected classrooms throughout the entire day (00:00-24:00) for the weekdays and weekend from the 10th of February to the 16th of February, 2018.

| **Temp.** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, all day** | max | 21.0 | 22.9 | 21.6 | 22.3 | 24.0 | 21.5 | 20.9 | 18.0 |
| | min | 18.4 | 20.0 | 17.8 | 18.8 | 19.9 | 18.3 | 18.1 | 10.1 |
| | mean | 19.6 | 21.2 | 19.6 | 20.1 | 21.8 | 19.6 | 19.3 | 14.0 |
| | st. dev. | 0.7 | 0.8 | 1.0 | 0.9 | 1.3 | 0.8 | 0.7 | 2.3 |
| | fluct. | 2.6 | 2.9 | 3.9 | 3.6 | 4.1 | 3.2 | 2.8 | 7.9 |
| **Weekend, all day** | max | 19.7 | 21.3 | 20.5 | 20.3 | 21.4 | 20.0 | 19.9 | 18.6 |
| | min | 18.8 | 20.3 | 18.9 | 19.2 | 20.1 | 18.9 | 18.7 | 12.3 |
| | mean | 19.3 | 20.8 | 19.5 | 19.6 | 20.6 | 19.5 | 19.3 | 15.1 |
| | st. dev. | 0.2 | 0.3 | 0.4 | 0.3 | 0.3 | 0.3 | 0.3 | 1.8 |
| | fluct. | 0.9 | 1.0 | 1.5 | 1.1 | 1.3 | 1.1 | 1.2 | 6.3 |

Table 14.4. Recorded mean values of relative humidity respectively in all selected classrooms throughout the entire day (00:00-24:00) for the weekdays and weekend from the 10th of February to the 16th of February, 2018.

| **RH** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, all day** | max | 58.3 | 56.6 | 60.9 | 57.8 | 48.5 | 61.1 | 58.5 | 86.1 |
| | min | 45.8 | 43.9 | 45.8 | 46.7 | 41.7 | 48.0 | 45.0 | 56.9 |
| | mean | 51.2 | 49.3 | 52.1 | 53.2 | 45.6 | 53.2 | 50.9 | 73.1 |
| | st. dev. | 3.2 | 2.6 | 4.1 | 2.6 | 2.0 | 2.7 | 3.7 | 7.9 |
| | fluct. | 12.5 | 12.6 | 15.1 | 11.1 | 6.8 | 13.1 | 13.5 | 29.3 |
| **Weekend, all day** | max | 66.5 | 57.7 | 65.8 | 61.1 | 51.9 | 61.5 | 68.1 | 89.5 |
| | min | 55.4 | 53.5 | 54.9 | 58.7 | 49.0 | 55.9 | 53.8 | 71.0 |
| | mean | 60.4 | 55.4 | 59.6 | 59.8 | 50.2 | 58.4 | 60.1 | 81.0 |
| | st. dev. | 3.5 | 1.2 | 3.6 | 0.8 | 0.9 | 1.5 | 4.4 | 4.7 |
| | fluct. | 11.1 | 4.3 | 10.9 | 2.4 | 2.8 | 5.6 | 14.3 | 18.5 |

*14.2.1.2. Period of recording and analysis of thermal behaviour from the 31st of March to the 06th of April, 2018*

In the following graphical representations (Figure 14.6), the mean values of temperature and relative humidity are presented in each orientation with same roof exposure for the whole week and weekend throughout the day (00:00-24:00).

It is important to note that this period was specifically selected for analysis because no technical system was provided in classrooms to modify the results.

The mean maximum outdoor temperature during the week is 25.5°C. The highest mean maximum temperature during the week throughout the whole day analysis is exhibited in the west-oriented classroom with a value of 23.7 °C, i.e. 1.2 °C higher from the lowest maximum temperature in south orientation with a value of 22.9 °C. The mean maximum temperature of north and east-oriented classrooms is at 23.4 °C and 21.5 °C. The high temperatures in west and north orientation are attributed to the absence of shading devices in both the west windows and south clerestories,. The mean minimum outdoor temperature during the week is 13.3 °C. Respectively, the highest minimum temperature during the week throughout the whole day analysis, is exhibited in the west-oriented classroom with a value of 22.0 °C, followed by the north-oriented classroom with a value of 21.9 °C and the south-oriented classroom with a value of 21.2 °C. The lowest minimum temperature during the week is  observed in the east-oriented classroom with a value of 20.8 °C. During the week, the mean indoor temperature fluctuation ranges from 1.3 to 2.1 °C, while the mean outdoor temperature fluctuation is 12.2°C.

The mean maximum outdoor temperature during the weekend is 25.2°C. The highest mean maximum temperature during the weekend throughout the whole day analysis is exhibited again in the west-oriented classroom with a value of 23.2 °C, i.e. 1.0°C higher from the lowest maximum temperature appeared in south orientation with a value of 22.2 °C. The mean maximum temperature of the north and east-oriented classrooms is at 22.9 °C and 22.4 °C. The mean minimum outdoor temperature during the weekend is 13.1 °C. Respectively, the highest minimum temperature during the weekend throughout the whole day analysis is exhibited in the west-oriented classroom with a value of 21.7°C, followed by the north-oriented classroom with a value of 21.2 °C and the south-oriented classroom with a value of 20.8 °C. The lowest minimum temperature during the weekend is observed in the east-oriented classroom with a value of 20.5 °C. During the weekend, the mean indoor temperature fluctuation ranges from 1.4 to 1.9 °C while, the mean outdoor temperature fluctuation is 12.2°C.

The mean maximum outdoor relative humidity during the week is 67.7%. The highest mean maximum relative humidity during the week throughout the whole day analysis is exhibited in the north-oriented classroom with a value of 52.6%, i.e. 11.2% higher from the lowest maximum relative humidity exhibited in west orientation with a value of 41.4%. The mean maximum relative humidity of the south and east-oriented classrooms is at 42.4% and 43.9%. The mean minimum outdoor relative humidity during the week is 21%. The highest minimum relative humidity during the week throughout the whole day analysis is observed in the north-oriented classroom with a value of 44.8%, followed by the west-oriented classroom with a value of 33.7% and the south-oriented classroom with a value of 33.1%. The lowest minimum relative humidity during the week is exhibited in the east-oriented classroom with a value of 23.3% because of the lowest temperatures recorded in this classroom. During the week, the mean indoor relative humidity fluctuation ranges from 7.7% to 20.6%, while the mean outdoor relative humidity fluctuation is from 46.7%. It is worth mentioning that the minimum relative humidity of the east-oriented classroom seems to reach values lower than 15% but due to the restriction of the monitoring equipment that only covers values from 15% to 95% it is difficult to identify the lowest level.

The mean maximum outdoor relative humidity during the weekend is 81.5%. The highest mean maximum relative humidity during the weekend throughout the whole day analysis is exhibited in the north-oriented classroom with a value of 57.8%, i.e. 13.1% higher from the lowest maximum relative humidity observed in west orientation with a value of 44.7%. The mean maximum relative humidity of the east and south-oriented classrooms is at 52.9% and 49.4%. The mean minimum outdoor relative humidity during the weekend is 30%. The highest minimum relative humidity during the weekend throughout the whole day analysis is exhibited in the north oriented classroom with a value of 47.5%, followed by the south-oriented classroom with a value of 41.3% and the west-oriented classroom with a value of 38.5%. The lowest minimum temperature during the weekend is observed in the east-oriented classroom with a value of 33.3%. During the weekend, the mean indoor relative humidity fluctuation ranges from 6.2% to 19.6%, while the mean outdoor relative humidity fluctuation is 51.5%.


Figure 14.6. Comparative evaluation of mean temperature and relative humidity of classrooms throughout the whole week and weekend during the entire day for the period of recording from the 31st of March to the 4th of April, 2018.

From Figure 14.7 and Figure 14.8 which show the temperature and relative humidity distribution of classrooms with same roof exposure (to the outside environment) in different orientations, several conclusions can be derived for the change of values within 24hours.

The highest mean temperature values during the occupied period appear in the west-oriented classroom due to the unshaded windows during both the entire week and weekend. During the week, the mean average value of air temperature of the west-oriented classroom is 22.5 °C, while the second highest mean average air temperature appears in the north orientation with a value of 22.1 °C. The south-oriented classroom has a mean average value of 21.8 °C and the east-oriented classroom has a 21.6 °C. The maximum temperatures in the west and the east-oriented classrooms are observed at around 16:00-17:00, in the north-oriented classroom at 23:00-00:00, and in the south-oriented classroom at around 14:00-16:00. It is interesting to see the different peak times in different orientations. The lowest mean minimum temperature is in the west, east and south-oriented classrooms at around 06:00 – 07:00, and in the north-oriented classroom at around 10:00.

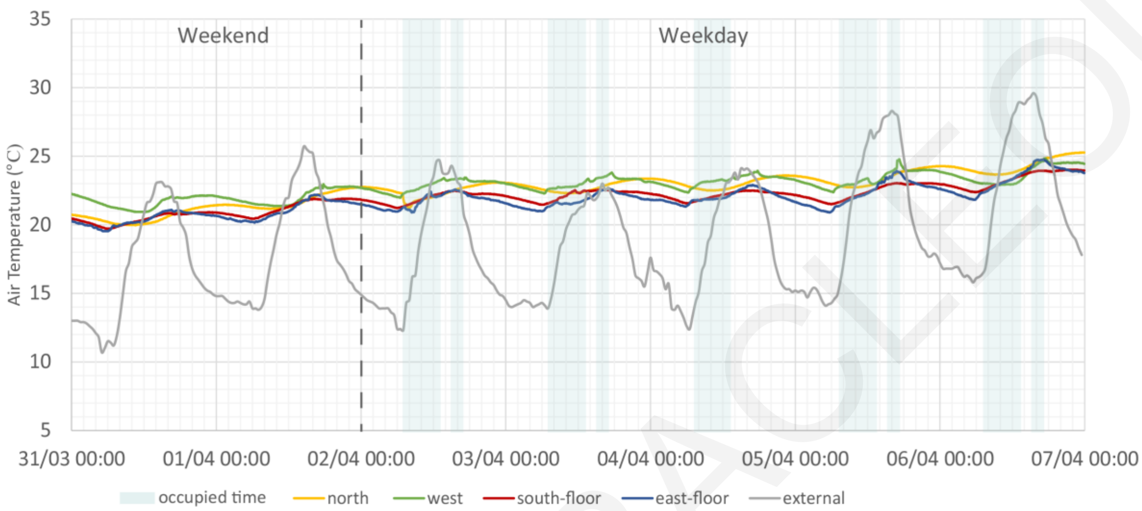



Figure 14.7. Temperature distribution of classrooms with same roof exposure in different orientations from the 31st of March to the 6th of April, 2018.

The highest mean relative humidity values during the occupied period are exhibited in the north-oriented classroom during the entire week as well as during the weekend. During the entire week, the mean average value of relative humidity of the north-oriented classroom is 47.4%, while the second highest mean average relative humidity appears in the west orientation with a value of 39%. The south-oriented classroom has a mean average value of 37.3% and the east-oriented classroom has a value of 31.1%. The minimum relative humidity values in all orientations are observed at around 16:00 during weekdays and at around 12:00-14:00 during the weekend. The maximum relative humidity values are exhibited during nighttime at around 00:00 which respond to the external relative humidity.

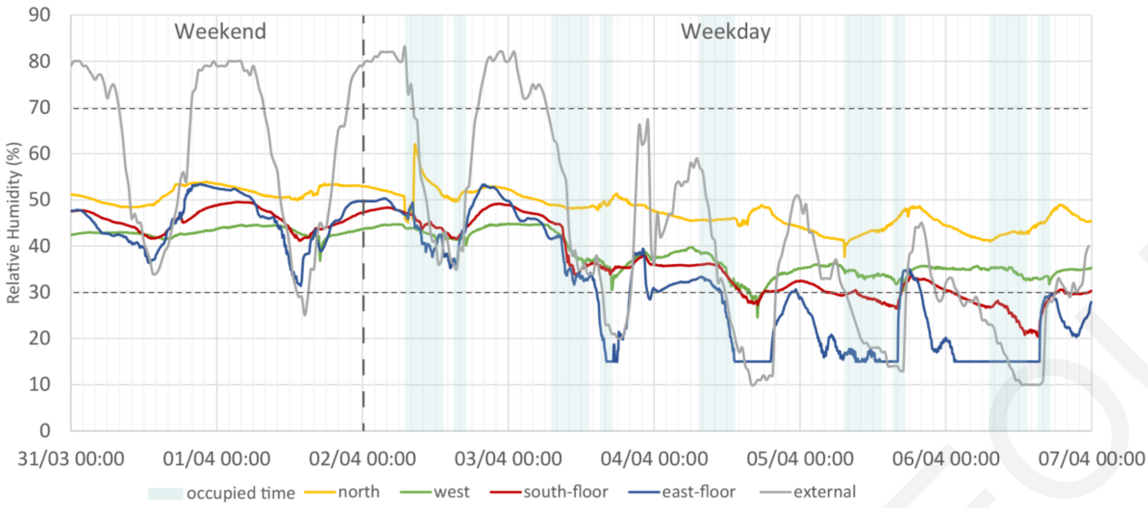



Figure 14.8. Relative humidity distribution of classrooms with same roof exposure in different orientations from the 31st of March to the 6th of April, 2018. Dashed line indicates the acceptable limits.

Figure 14.9 shows various comparative evaluations of air temperature in classrooms during the intermediate period. Specifically, comparisons made (a) in classrooms with same orientations and different roof exposure, (b) in classrooms with the same orientation but different design elements in terms of sun protection, and (c) in classrooms with different orientations and same roof exposure.

In Figure 14.9 (a), the comparison is made between classrooms in east orientation with different roof exposure, i.e. one is located on the ground floor covered by the classroom on the first floor and the second is located on the first floor having its roof exposed to the external environment. As shown, the east-oriented classroom on the first floor has slightly higher temperatures compared to the classroom on the ground floor. This is attributed to the higher level and intensity of solar radiation during the intermediate period which leads to higher heat gains of the first floor through the roof. The mean average temperature during the occupied period of the entire week is 21.2°C in the ground floor, while it is 21.6°C in the first floor.

In a similar context, a south-oriented classroom of the ground floor is compared with a south-oriented classroom on the first floor in Figure 13.8 b. As shown, the south-oriented classroom on the first floor has higher temperatures compared to the classroom on the ground floor with a difference of the mean values during occupied period of 0.8°C. Specifically, the mean average temperatures during the occupied period are 21.0°C and 21.8°C in the ground and first floor classrooms, respectively. This is also attributed to the fact that first floor receives heat gains through the roof, as the temperature outside is higher than inside.

In Figure 14.9.b a comparison is also made in classrooms with the same orientation and roof exposure but different design elements in terms of sun protection. Specifically, comparison is made between the classroom in the south orientation of the first floor and the classroom located on the ground floor with its roof exposed to the external environment and a horizontal louver of 0.50m depth as a shading system of south openings and the overhang of 2.00m located on the north side. The classroom with the differentiated design elements shows significantly higher mean temperatures during the recording period with a value of 22.9 °C, 1.1°C higher compared to the typical south-oriented classroom. This is attributed to the unshaded windows in the south compared to the typical classroom that has an overhang in front of large windows.

Finally, in Figure 14.9.c comparison is made in classrooms with same roof exposure and different orientation, i.e. the south classroom on the ground floor and the east classroom on the ground floor. As shown, the south-oriented classroom has slightly lower temperatures compared to the east-oriented classroom. This is attributed to the fact that the south-oriented classroom has the proper shading system for its orientation which is the overhang blocking some solar radiation, whereas the overhang in the east-oriented classroom is not the proper one to block the sun is at lower attitude. Specifically, the mean average temperature of the east-oriented classroom is 0.2°C higher than the south-oriented classroom during the occupied time with a value of 21.2°C compared to 21.0°C found in the east-oriented classroom.

Figure 14.10 shows the relative humidity distribution of the abovementioned comparisons. The relationship between temperature and relative humidity is inversely proportional.

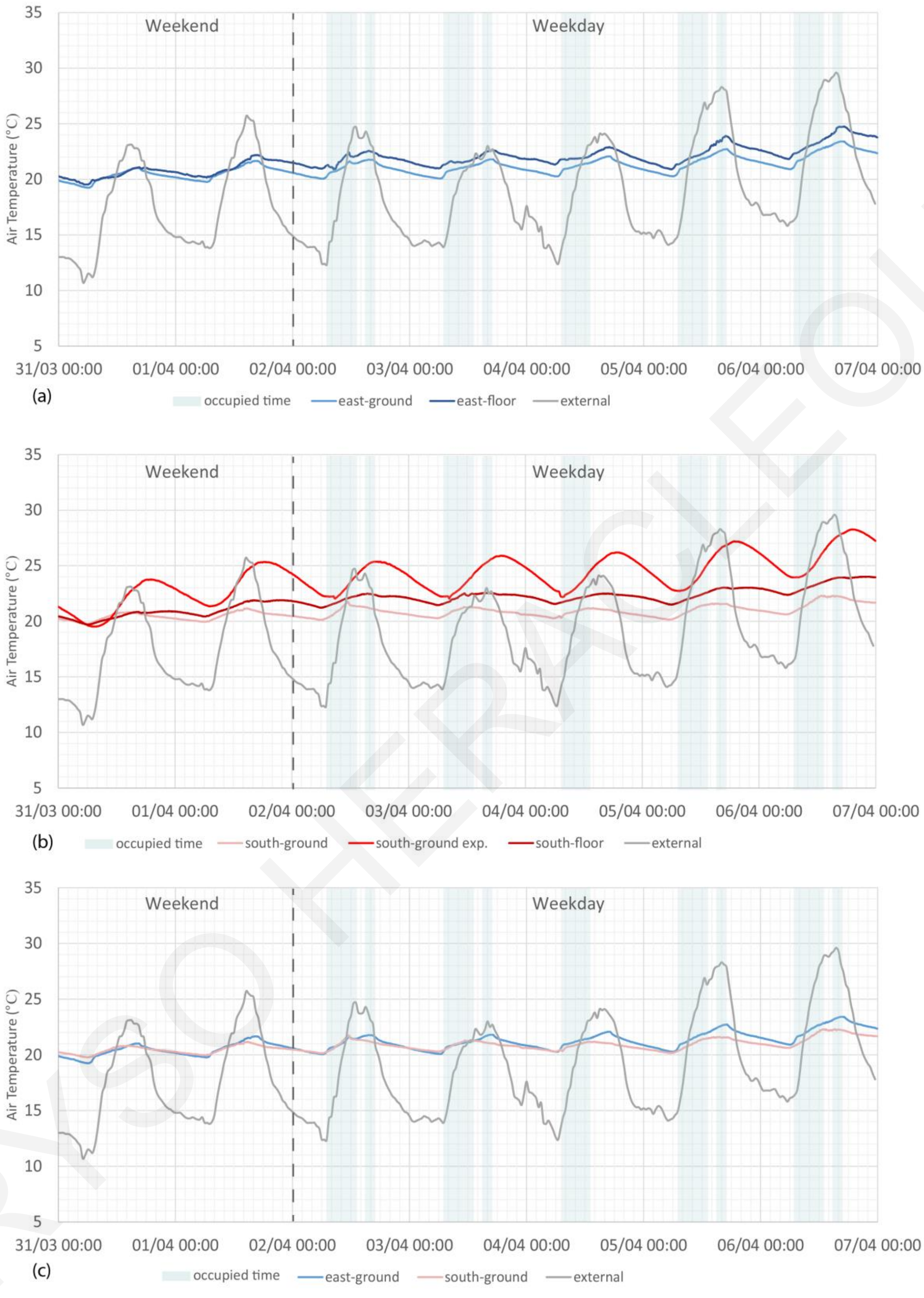



Figure 14.9. Comparison of air temperature made in (a) classrooms with same orientations and different roof exposure (east), (bi) classrooms with same orientations and different roof exposure (south) and (bii) classrooms with the same orientation (south) but different sun protection design elements, and (c) in classrooms with different orientations (east and south) and same roof exposure, from the 31st of March to the 6th of April, 2018.

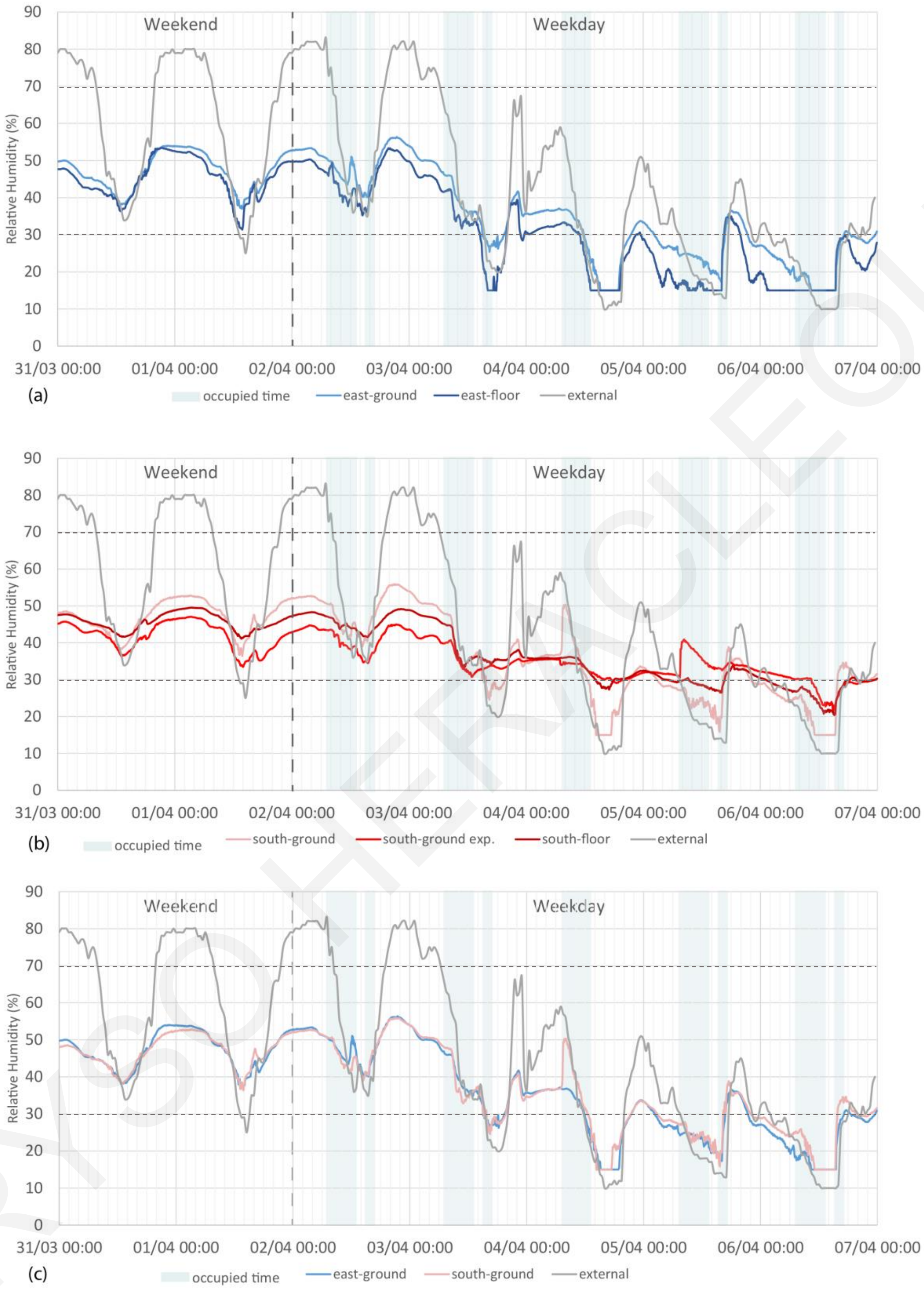



Figure 14.10. Comparison of relative humidity made in (a) classrooms with same orientations and different roof exposure (east), (bi) classrooms with same orientations and different roof exposure (south) and (bii) classrooms with the same orientation (south) but different sun protection design elements, and (c) in classrooms with different orientations (east and south) and same roof exposure from the 31st of March to the 6th of April, 2018. Dashed line indicates the acceptable limits.

Table 14.5 and Table 14.6 summarize the recorded values of mean air temperature and relative humidity respectively, in all selected classrooms during the occupied period (07:30-13:35) both for the whole week and weekend from the 31st of March to the 6th of April, 2018. Table 14.7 and Table 14.8 summarize the recorded values of mean air temperature and relative humidity respectively in all selected classrooms throughout the entire day (00:00-24:00) for both the whole week and weekend from the 31st of March to the 6th of April, 2018.

Table 14.5. Recorded mean values of air temperature in all selected classrooms during the occupied period (07:30-13:35) both for the whole week and weekend from the 31st of March to the 4th of April, 2018.

| **Temp.** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, occupied time** | max | 21.6 | 21.4 | 24.4 | 22.3 | 22.8 | 22.2 | 22.2 | 24.6 |
| | min | 20.7 | 20.4 | 22.0 | 21.9 | 22.3 | 21.4 | 21.2 | 14.6 |
| | mean | 21.2 | 21.0 | 22.9 | 22.1 | 22.5 | 21.8 | 21.6 | 20.6 |
| | st. dev. | 0.3 | 0.3 | 0.8 | 0.1 | 0.1 | 0.3 | 0.3 | 3.4 |
| | fluct. | 1.0 | 1.0 | 2.5 | 0.4 | 0.6 | 0.9 | 1.0 | 10.1 |
| | | | | | | | | | |
| **Weekend, occupied time** | max | 21.4 | 21.4 | 24.1 | 21.8 | 22.6 | 22.0 | 22.0 | 24.4 |
| | min | 20.4 | 20.2 | 21.7 | 21.2 | 21.9 | 21.0 | 20.6 | 14.2 |
| | mean | 20.9 | 20.9 | 22.6 | 21.5 | 22.1 | 21.5 | 21.3 | 19.8 |
| | st. dev. | 0.3 | 0.3 | 0.8 | 0.2 | 0.2 | 0.3 | 0.4 | 3.6 |
| | fluct. | 1.1 | 1.1 | 2.4 | 0.7 | 0.7 | 1.0 | 1.3 | 10.3 |

Table 14.6. Recorded mean values of relative humidity in all selected classrooms during the occupied period (07:30-13:35) both for the whole week and weekend from the 31st of March to the 4th of April, 2018.

| **RH** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, occupied time** | max | 39.0 | 42.5 | 39.7 | 49.1 | 40.5 | 40.0 | 35.2 | 56.1 |
| | min | 30.1 | 29.8 | 31.8 | 45.5 | 36.9 | 34.1 | 26.0 | 25.6 |
| | mean | 35.2 | 36.1 | 36.6 | 47.4 | 39.0 | 37.3 | 31.1 | 38.8 |
| | st. dev. | 2.9 | 4.1 | 2.5 | 0.9 | 1.1 | 1.9 | 3.0 | 10.6 |
| | fluct. | 8.9 | 12.6 | 7.9 | 3.6 | 3.6 | 5.9 | 9.2 | 30.6 |
| | | | | | | | | | |
| **Weekend, occupied time** | max | 50.2 | 50.2 | 44.0 | 56.6 | 44.2 | 47.5 | 47.9 | 73.5 |
| | min | 39.7 | 39.0 | 35.2 | 47.5 | 42.1 | 42.1 | 34.7 | 32.5 |
| | mean | 45.9 | 45.2 | 40.5 | 52.1 | 43.5 | 45.1 | 41.7 | 51.5 |
| | st. dev. | 3.1 | 3.5 | 2.8 | 2.1 | 0.6 | 1.6 | 4.2 | 14.1 |
| | fluct. | 10.5 | 11.3 | 8.7 | 9.0 | 2.1 | 5.4 | 13.3 | 41.0 |

Table 14.7. Recorded mean values of air temperature in all selected classrooms throughout the entire day (00:00-24:00) for both the whole week and weekend from the 31st of March to the 4th of April, 2018.

| **Temp.** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, all day** | max | 22.1 | 21.4 | 26.0 | 23.4 | 23.7 | 22.5 | 22.9 | 25.5 |
| | min | 20.1 | 20.2 | 22.0 | 21.9 | 22.0 | 21.2 | 20.8 | 13.3 |
| | mean | 21.1 | 20.8 | 24.0 | 22.6 | 22.8 | 21.9 | 21.8 | 18.7 |
| | st. dev. | 0.6 | 0.4 | 1.4 | 0.5 | 0.5 | 0.4 | 0.6 | 4.2 |
| | fluct. | 2.0 | 1.3 | 4.0 | 1.5 | 1.7 | 1.3 | 2.1 | 12.2 |
| **Weekend, all day** | max | 21.7 | 21.5 | 25.3 | 22.9 | 23.2 | 22.2 | 22.4 | 25.2 |
| | min | 19.9 | 20.0 | 21.7 | 21.2 | 21.7 | 20.8 | 20.5 | 13.1 |
| | mean | 20.8 | 20.7 | 23.6 | 22.1 | 22.4 | 21.6 | 21.4 | 17.9 |
| | st. dev. | 0.6 | 0.4 | 1.3 | 0.5 | 0.5 | 0.5 | 0.6 | 4.0 |
| | fluct. | 1.8 | 1.4 | 3.7 | 1.8 | 1.5 | 1.4 | 1.9 | 12.2 |

Table 14.8. Recorded mean values of air temperature in all selected classrooms throughout the entire day (00:00-24:00) for both the whole week and weekend from the 31st of March to the 4th of April, 2018.

| **RH** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, all day** | max | 39.0 | 42.5 | 39.7 | 49.1 | 40.5 | 40.0 | 35.2 | 56.1 |
| | min | 30.1 | 29.8 | 31.8 | 45.5 | 36.9 | 34.1 | 26.0 | 25.6 |
| | mean | 35.2 | 36.1 | 36.6 | 47.4 | 39.0 | 37.3 | 31.1 | 38.8 |
| | st. dev. | 2.9 | 4.1 | 2.5 | 0.9 | 1.1 | 1.9 | 3.0 | 10.6 |
| | fluct. | 8.9 | 12.6 | 7.9 | 3.6 | 3.6 | 5.9 | 9.2 | 30.6 |
| **Weekend, all day** | max | 50.2 | 50.2 | 44.0 | 56.6 | 44.2 | 47.5 | 47.9 | 73.5 |
| | min | 39.7 | 39.0 | 35.2 | 47.5 | 42.1 | 42.1 | 34.7 | 32.5 |
| | mean | 45.9 | 45.2 | 40.5 | 52.1 | 43.5 | 45.1 | 41.7 | 51.5 |
| | st. dev. | 3.1 | 3.5 | 2.8 | 2.1 | 0.6 | 1.6 | 4.2 | 14.1 |
| | fluct. | 10.5 | 11.3 | 8.7 | 9.0 | 2.1 | 5.4 | 13.3 | 41.0 |

*14.2.1.3. Period of recording and analysis of thermal behaviour from the 19th of May to the 25th of May 2018*

In the following graphical representations (Figure 14.11), the mean values of temperature and relative humidity are presented in each orientation with same roof exposure for the whole week and weekend throughout the day (00:00-24:00).

This period was selected for analysis as it represents the hottest period of the teaching term, with extreme external conditions. Moreover, it should be noted that north and west oriented classrooms use air conditioning in selected periods of the day influencing the results. However, the analysis during the weekend helps to understand the behaviour of classrooms better.

The mean maximum outdoor temperature during the week is 35.4°C. The highest mean maximum temperature during the week throughout the whole day analysis, is observed in the south-oriented classroom with a value of 33.3°C, i.e. 0.7 °C higher from the lowest maximum temperature observed in the west orientation with a value of 32.6 °C. The mean maximum temperature of the north and the east-oriented classrooms is at 32.7 °C. The high temperatures in the south orientation are attributed to the exposure of the roof to the high-intensity solar radiation. The mean minimum outdoor temperature during the week is 23.1 °C. Respectively, the highest minimum temperature during the week throughout the whole day analysis is exhibited in the south-oriented classroom with a value of 31.4 °C, followed by the east-oriented classroom with a value of 30.6 °C and the north-oriented classroom with a value of 29 °C. The lowest minimum temperature during the week is recorded in the west-oriented classroom with a value of 18.7 °C. It should be noted that the west and north-oriented classrooms uses air-conditioning in specific periods, therefore affecting the results. During the week, the mean indoor temperature fluctuation ranges from 1.9 to 3.9 °C, while the mean outdoor temperature fluctuation is 12.3°C.

The mean maximum outdoor temperature during the weekend is 37.4°C. The highest mean maximum temperature during the weekend throughout the whole day analysis is observed again in the south-oriented classroom with a value of 33.6 °C, i.e. 0.5°C higher from the lowest maximum temperature observed in the east orientation with a value of 33.1 °C. The mean maximum temperature of the north and west-oriented classrooms is at 33.3 °C and 33.2 °C. The mean minimum outdoor temperature during the weekend is 24.1 °C. Respectively, the highest minimum temperature during the weekend throughout the whole day analysis is observed in the south-oriented classroom with a value of 31.5°C, followed by the north-oriented classroom with a value of 31 °C and the east-oriented classroom with a value of 30.7°C. The lowest minimum temperature during the weekend is recorded in the west-oriented classroom with a value of 30.2 °C. During the weekend, the mean indoor temperature fluctuation ranges from 2.1 to 3°C; while, the mean outdoor temperature fluctuation is 13.3°C. There is a slight fluctuation of temperatures during the 24 hours as a result of the heavy-weighted structure and consequently the increased thermal inertia of the building. In addition, the absence of night cooling does not allow the building envelope to cool down during the evening hours when the ambient temperatures are lower.

The mean maximum outdoor relative humidity during week is 67.7%. The highest mean maximum relative humidity during week throughout the whole day analysis is exhibited in the north-oriented classroom with a value of 41.9%, i.e. 5.3% higher from the lowest maximum relative humidity observed in west orientation with value 36.6%. The mean maximum relative humidity of the south and east-oriented classrooms is 38.4% and 41.1%. The mean minimum outdoor relative humidity during week is 21.9%. The highest minimum relative humidity during week throughout the whole day analysis is recorded in the north-oriented classroom with a value of 31%, followed by the west-oriented classroom with a value of 30% and the south-oriented classroom with a value of 24.4%. The lowest minimum relative humidity during the week is recorded in the east-oriented classroom with a value of 21.6%. During the week, the mean indoor relative humidity fluctuation ranges from 6.6% to 19.5%, while the mean outdoor relative humidity fluctuation is 45.9%. It is worth mentioning that the minimum relative humidity of the east-oriented classroom seems to reach values lower than 15% but due to the restriction of the monitoring equipment that only covers values from 15% to 95%, it is difficult to identify the lowest level.

The mean maximum outdoor relative humidity during the weekend is 57.5%. The highest mean maximum relative humidity during the weekend throughout the whole day analysis is evident in the north-oriented classroom with a value of 40%, i.e. 7.9% higher from the lowest maximum relative humidity exhibited in south orientation with a value of 34.7%. The mean maximum relative humidity of the east and west-oriented classrooms is 36.3% and 34.7%. The mean minimum outdoor relative humidity during the weekend is 16%. The highest minimum relative humidity during the weekend throughout the whole day analysis is observed in the north-oriented classroom with a value 32%, followed by the west-oriented classroom with a value of 28.6% and the south-oriented classroom with a value of 18.5%. The lowest minimum temperature during the weekend is observed in the east-oriented classroom with a value of 15.7%. During the weekend, the mean indoor relative humidity fluctuation ranges from 6.1% to 20.6%, while the mean outdoor relative humidity fluctuation is 41.5%.

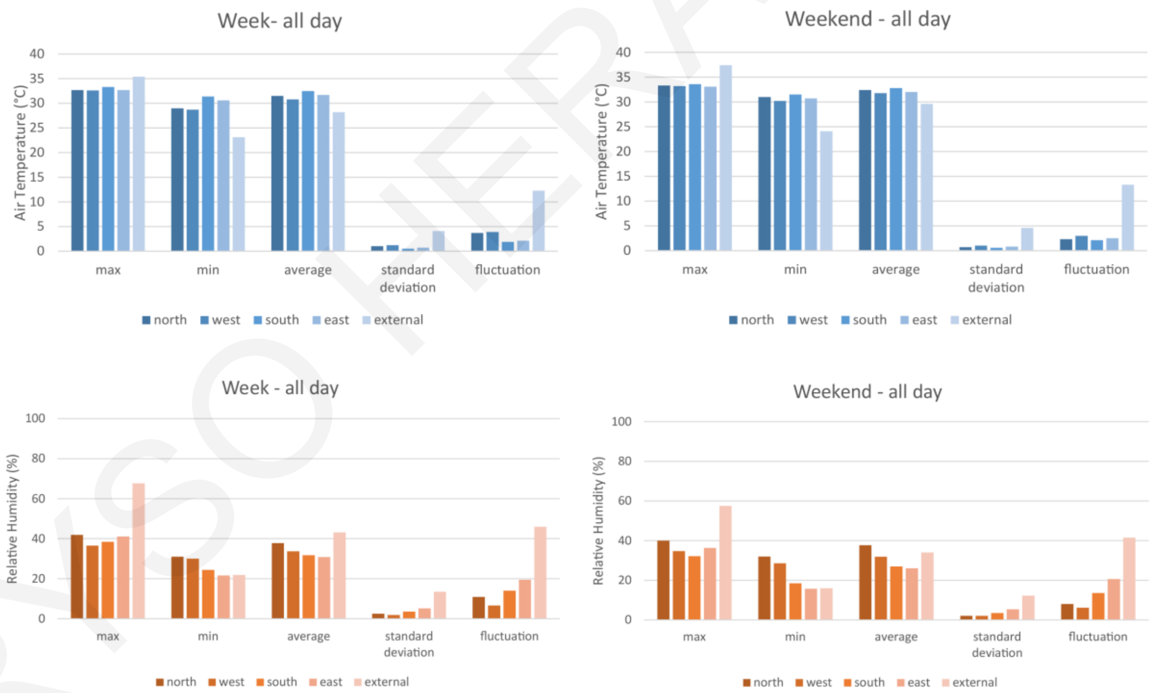



Figure 14.11. Comparative evaluation of mean temperature and relative humidity of classrooms throughout the whole week and weekend, during the entire day for the period of recording, from the 19th of May to the 25th of May, 2018.

From Figure 14.12 and Figure 14.13 which show the temperature and relative humidity distribution of classrooms with same roof exposure (to the outside environment) in different orientations, several conclusions can be derived for the change of values within 24hours.

The highest mean temperature values during occupied period are recorded in the south-oriented classroom due to extensive solar gain through the roof, during both the entire week and weekend. During the weekend where no technical system is provided, the mean average value of air temperature of the south-oriented classroom is 32.4 °C, while the second highest mean average air temperature appears in the east orientation with a value of 31.9 °C. The north-oriented classroom has a mean average value of 31.5 °C and the west-oriented classroom has a temperature of 30.6 °C. The maximum temperature in south, east and west-oriented classrooms are observed at around 18:00, while in the north-oriented classroom at 00:00. The lowest mean minimum temperature is exhibited in the south-oriented classroom at around 08:00, in the east at around 06:00, while in the west and north-oriented classrooms at around 10:00. During the week, air conditioning is provided in the north and west-oriented classrooms. During the occupied time of the entire week, the mean average value of air temperature of the south-oriented classroom is 32.0 °C, followed by the east and north-oriented classrooms with temperatures of 31.5 °C and 30.2°C respectively. The lowest mean average temperature appears in the west-oriented classroom with a value of 29.3 °C.

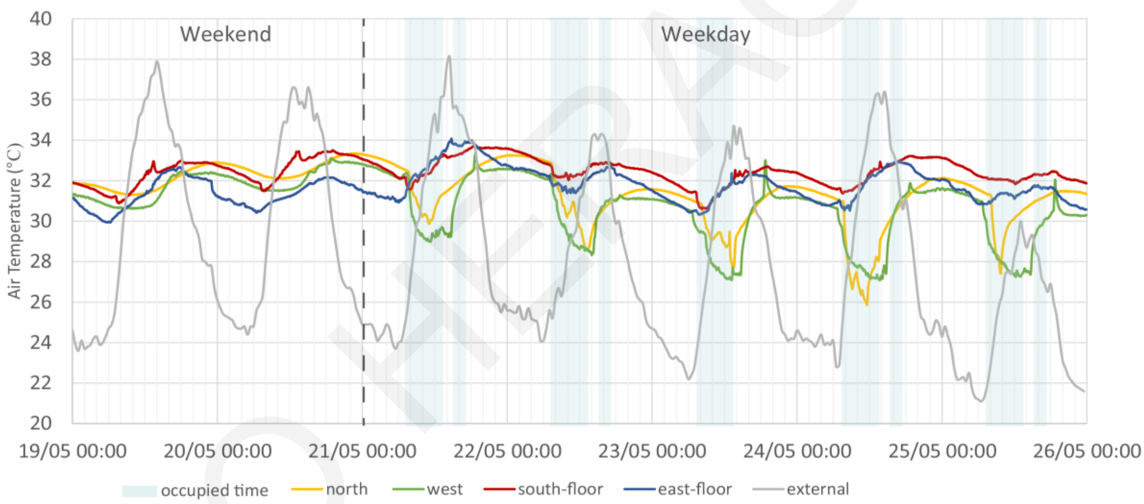



Figure 14.12. Temperature distribution of classrooms with same roof exposure in different orientations from the 19th of May to the 25th of May, 2018.

The highest mean relative humidity values during the occupied period are evident in the north-oriented classroom during the entire week and weekend. During the weekend, the mean average value of relative humidity of the north-oriented classroom is 32.1%, while the second highest mean average relative humidity appears in the west orientation with a value of 28.9%. The east-oriented classroom has a mean average value of 19.6% and the south-oriented classroom has a mean average temperature of 18.5%. The minimum relative humidity values in the east and south orientations are observed at around 12:00-14:00 and in the west and north-oriented classrooms at around 18:00 during weekends. During weekdays, due to technical systems in the north and west-oriented classrooms it is difficult to derive to a conclusion, as the minimum values were recorded during the time when the system was in operation.

The maximum values of relative humidity in the east, south and north-oriented classrooms are exhibited at around 00:00-02:00 while in the west-oriented classroom at around 06:00.

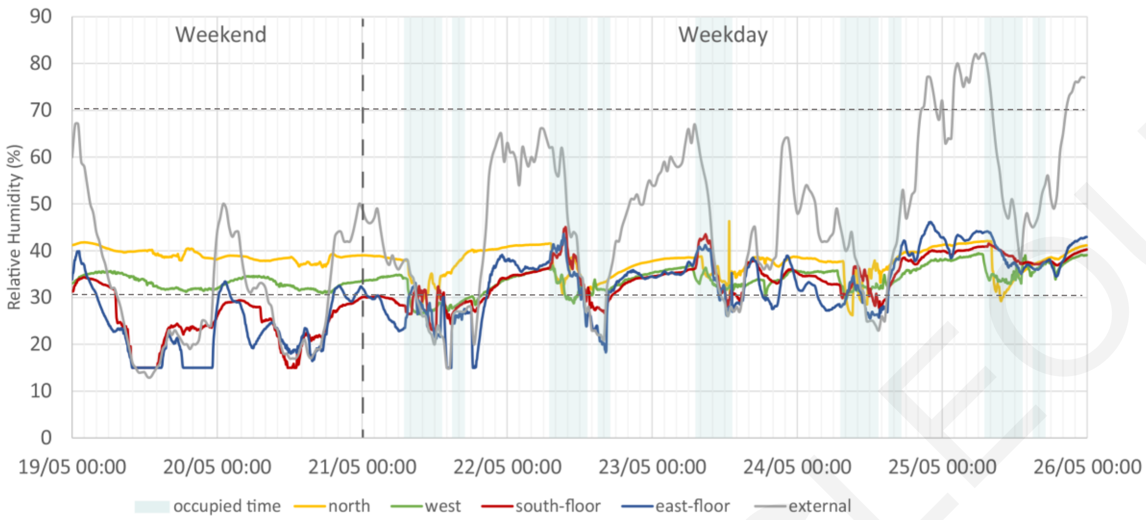



Figure 14.13. Relative humidity distribution of classrooms with same roof exposure in different orientations from the 19th of May to the 25th of May, 2018. Dashed line indicates the acceptable limits.

Figure 14.14 shows various comparative evaluations of air temperature in classrooms during the intermediate period. Specifically, comparisons are made between (a) classrooms with same orientations and different roof exposure, (b) classrooms with the same orientation but different design elements in terms of sun protection, and (c) classrooms with different orientations and same roof exposure.

In Figure 14.14 (a), the comparison is made between classrooms in east orientation with different roof exposure, i.e. one is located on the ground floor covered by the classroom on the first floor and the second is located on the first floor having its roof exposed to the external environment. As shown, the east-oriented classroom on the first floor has higher temperatures compared to the classroom on the ground floor. This is attributed to the higher level and intensity of solar radiation during the summer period which leads to higher solar gains for the first floor through the roof. The mean average temperature during the occupied period during the entire week is 30.2°C on the ground floor, while it is 31.5°C on the first floor.

In a similar context, a south-oriented classroom of the ground floor is compared to a south-oriented classroom on the first floor in Figure 13.8 b. As shown, the south-oriented classroom on the first floor has significantly higher temperatures compared to the classroom on the ground floor, with a 2.8°C difference of the mean values during occupied period . Specifically, the mean average temperatures during the occupied period are 29.2°C and 32.0°C on the ground and first floor classrooms respectively. This is again attributed to the fact that the first floor receives solar gains through the roof as the temperature outside is higher than the inside.

In Figure 14.14.b a comparison is also made between classrooms with the same orientation and roof exposure but different design elements in terms of sun protection. Specifically, comparison is made between the classroom in the south orientation of the first floor and the classroom located on the ground floor with its roof exposed to the external environment and a horizontal louver of 0.50m depth as a shading system of south openings and the 2.00m overhang located in the north side. The classroom with different structure shows significantly higher mean temperatures during the recording period with a value of 32.6 °C, i.e. 0.6°C higher compared to the classroom on the first floor. This is attributed to the unshaded windows in the south compared to the typical classroom that has an overhang in front of large windows.

Finally, in Figure 14.14.c comparison is made between classrooms with same roof exposure and different orientation, i.e. south classroom on the ground floor and east classroom on the ground floor. As shown, the south-oriented classroom has slightly lower temperatures compared to the east-oriented classroom. This is attributed to the fact that the south-oriented classroom has the proper shading system for its orientation, which is the overhang blocking some solar radiation, whereas the overhang of the east-oriented classroom is not the proper one as the sun is at a lower attitude. Specifically, the mean average temperature of the east oriented classroom is 1°C higher than the typical south-oriented classroom during the occupied time with a value of 29.2°C compared to 30.2°C recorded in the east-oriented classroom.

Figure 14.15 shows the relative humidity distribution of the abovementioned comparisons. The relationship between temperature and relative humidity is inversely proportional.

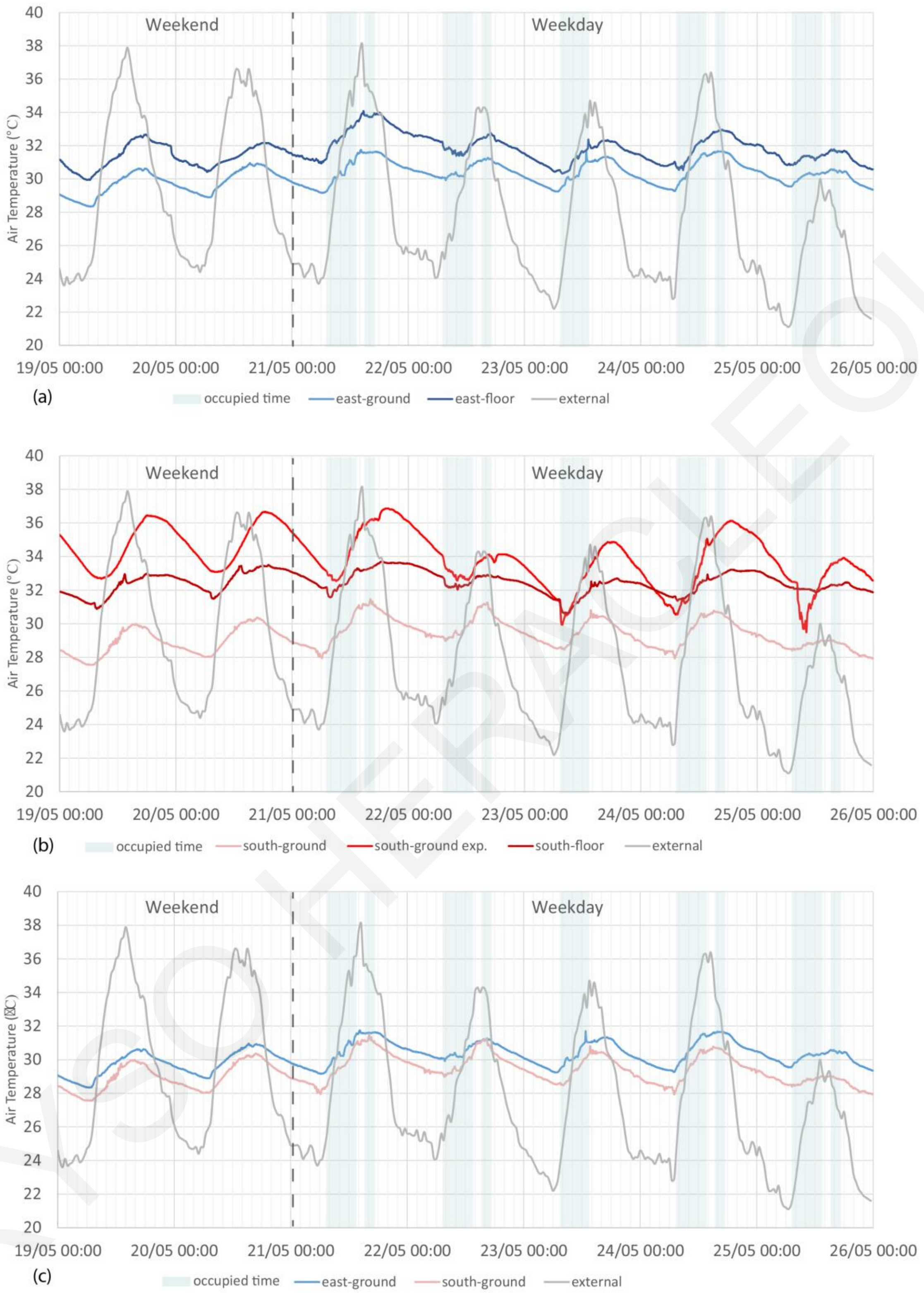



Figure 14.14. Comparison of air temperature made in (a) classrooms with same east orientations and different roof exposure, (bi) classrooms with same south orientations and different roof exposure and (bii) classrooms with the same south orientation but different design elements in terms of sun protection, and (c) in classrooms with different orientations (east and south) and same roof exposure from the 19th of May to the 25th of May, 2018.

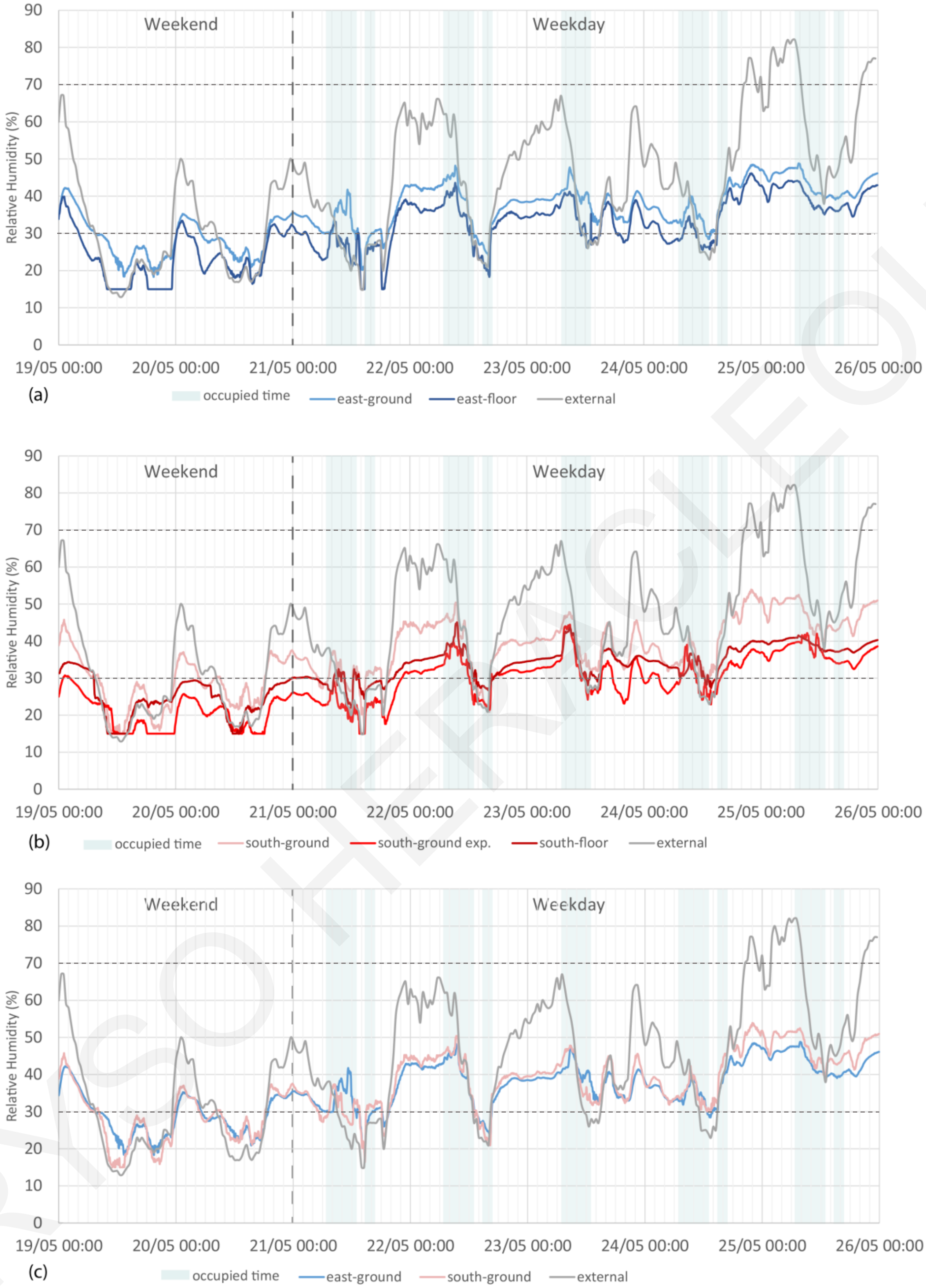



Figure 14.15. Comparison of relative humidity made in (a) classrooms with same east orientations and different roof exposure, (bi) classrooms with same south orientations and different roof exposure and (bii) classrooms with the same south orientation but different design elements in terms of sun protection, and (c) in classrooms with different orientations (east and south) and same roof exposure from the 19th of May to the 25th of May, 2018. Dashed line indicates the acceptable limits.

Table 14.9 and Table 14.10 summarize the recorded values of mean air temperature and relative humidity respectively in all selected classrooms during the occupied period (07:30-13:35) both for the whole week and weekend from the 31st of March to the 6th of April, 2018. Table 14.11 and Table 14.12 summarize the recorded values of mean air temperature and relative humidity respectively, in all selected classrooms throughout the entire day (00:00-24:00) for both the whole week and weekend from the 19th of May to the 25th of May, 2018.

Table 14.9. Recorded mean values of air temperature in all selected classrooms during the occupied period (07:30-13:35) both for the whole week and weekend from the 19th of May to the 25th of May, 2018.

| **Temp.** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South -floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week occupied time** | max | 31.0 | 30.2 | 34.2 | 31.7 | 30.8 | 32.8 | 32.2 | 34.8 |
| | min | 29.4 | 28.4 | 31.6 | 29.0 | 28.7 | 31.4 | 30.8 | 24.9 |
| | mean | 30.2 | 29.2 | 32.6 | 30.2 | 29.3 | 32.0 | 31.5 | 30.8 |
| | st. dev. | 0.4 | 0.5 | 0.8 | 0.7 | 0.5 | 0.4 | 0.4 | 3.2 |
| | fluct. | 1.6 | 1.8 | 2.6 | 2.7 | 2.1 | 1.4 | 1.4 | 9.9 |
| **Weekend, occupied time** | max | 31.1 | 30.5 | 35.1 | 32.4 | 32.0 | 33.4 | 32.5 | 35.4 |
| | min | 29.2 | 28.3 | 32.8 | 31.0 | 30.2 | 31.5 | 31.1 | 23.1 |
| | mean | 30.2 | 29.4 | 33.5 | 31.5 | 30.6 | 32.4 | 31.9 | 28.2 |
| | st. dev. | 0.5 | 0.6 | 0.7 | 0.4 | 0.4 | 0.6 | 0.4 | 4.1 |
| | fluct. | 1.9 | 2.2 | 2.3 | 1.4 | 1.8 | 1.8 | 1.4 | 12.3 |

Table 14.10. Recorded mean values of relative humidity in all selected classrooms during the occupied period (07:30-13:35) both for the whole week and weekend from the 19th of May to the 25th of May, 2018.

| **RH** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, occupied time** | max | 40.8 | 41.7 | 34.3 | 40.3 | 35.5 | 35.6 | 35.0 | 50.0 |
| | min | 28.4 | 27.4 | 22.1 | 31.2 | 30.5 | 24.9 | 23.5 | 23.4 |
| | mean | 35.0 | 34.2 | 28.4 | 35.2 | 32.3 | 30.2 | 29.2 | 34.6 |
| | st. dev. | 3.6 | 4.6 | 3.9 | 2.1 | 1.2 | 3.5 | 3.6 | 9.2 |
| | fluct. | 12.3 | 14.3 | 12.3 | 9.0 | 5.0 | 10.8 | 11.4 | 26.6 |
| **Weekend, occupied time** | max | 35.3 | 33.9 | 25.9 | 38.3 | 34.2 | 29.0 | 28.9 | 35.5 |
| | min | 25.3 | 24.0 | 16.6 | 32.1 | 28.9 | 18.5 | 19.6 | 18.5 |
| | mean | 30.3 | 28.7 | 21.1 | 35.2 | 30.4 | 24.2 | 24.3 | 24.7 |
| | st. dev. | 3.1 | 3.3 | 2.8 | 1.4 | 1.1 | 3.7 | 2.9 | 5.9 |
| | fluct. | 9.9 | 9.9 | 9.3 | 6.2 | 5.2 | 10.5 | 9.3 | 17.0 |

Table 14.11. Recorded mean values of air temperature respectively in all selected classrooms throughout the entire day (00:00-24:00) for both the whole week and weekend from the 19th of May to the 25th of May, 2018.

| **Temp.** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, all day** | max | 31.2 | 30.6 | 36.0 | 32.7 | 32.6 | 33.3 | 32.7 | 35.4 |
| | min | 29.2 | 28.1 | 31.6 | 29.0 | 28.7 | 31.4 | 30.6 | 23.1 |
| | mean | 30.2 | 29.3 | 34.0 | 31.5 | 30.8 | 32.5 | 31.7 | 28.2 |
| | st. dev. | 0.6 | 0.7 | 1.3 | 1.0 | 1.2 | 0.5 | 0.7 | 4.1 |
| | fluct. | 2.1 | 2.5 | 4.5 | 3.7 | 3.9 | 1.9 | 2.1 | 12.3 |
| **Weekend, all day** | max | 31.4 | 30.9 | 36.8 | 33.3 | 33.2 | 33.6 | 33.1 | 37.4 |
| | min | 29.0 | 28.0 | 32.8 | 31.0 | 30.2 | 31.5 | 30.7 | 24.1 |
| | mean | 30.2 | 29.4 | 34.9 | 32.4 | 31.8 | 32.8 | 32.0 | 29.6 |
| | st. dev. | 0.8 | 0.9 | 1.3 | 0.7 | 1.0 | 0.6 | 0.8 | 4.6 |
| | fluct. | 2.3 | 2.9 | 3.9 | 2.3 | 3.0 | 2.1 | 2.5 | 13.3 |

Table 14.12. Recorded mean values of relative humidity respectively in all selected classrooms throughout the entire day (00:00-24:00) for both the whole week and weekend from the 19th of May to the 25th of May, 2018.

| **RH** | | **East-ground** | **South-ground** | **South-ground exp.** | **North** | **West** | **South-floor** | **East-floor** | **External** |
|---|---|---|---|---|---|---|---|---|---|
| **Week, all day** | max | 44.8 | 47.6 | 36.2 | 41.9 | 36.6 | 38.4 | 41.1 | 67.7 |
| | min | 26.1 | 24.8 | 20.7 | 31.0 | 30.0 | 24.4 | 21.6 | 21.9 |
| | mean | 35.5 | 36.5 | 28.0 | 37.8 | 33.7 | 31.7 | 30.8 | 43.2 |
| | st. dev. | 4.8 | 5.9 | 4.0 | 2.5 | 1.9 | 3.6 | 5.2 | 13.5 |
| | fluct. | 18.7 | 22.8 | 15.5 | 10.9 | 6.6 | 14.0 | 19.5 | 45.9 |
| **Weekend, all day** | max | 39.2 | 41.4 | 28.9 | 40.0 | 34.7 | 32.1 | 36.3 | 57.5 |
| | min | 20.5 | 18.7 | 15.0 | 32.0 | 28.6 | 18.5 | 15.7 | 16.0 |
| | mean | 31.0 | 31.2 | 22.2 | 37.7 | 31.9 | 27.0 | 26.1 | 34.0 |
| | st. dev. | 4.6 | 5.2 | 3.7 | 2.0 | 2.0 | 3.5 | 5.3 | 12.2 |
| | fluct. | 18.7 | 22.7 | 13.9 | 8.0 | 6.1 | 13.6 | 20.6 | 41.5 |

### *14.2.2. Second series of measurements recording operative temperature*

The second series of measurements aims to evaluate the thermal comfort using equipment that is more specialized and to examine the behaviour of educational buildings under a range of diverse ventilation strategies in relation to window opening configurations. The results of various ventilation strategies are analysed extensively in **Chapter 15.2.**

#### *14.2.2.1. Wind speed*

The recordings of the outdoor wind environment show that the prevailing daytime wind flow (07:30-13:30) during the winter period is mainly north-oriented with an average wind speed of 1.6 m/s (Fig.13.16). During the summer period, the prevailing daytime wind flow (07:30-13:30) is north-east-oriented (NNE 23°), while the prevailing night time wind flow (21:00-07:00) is west-oriented. The average wind speed is 1.5 m/s and 1.7 m/s during the day and night time respectively.

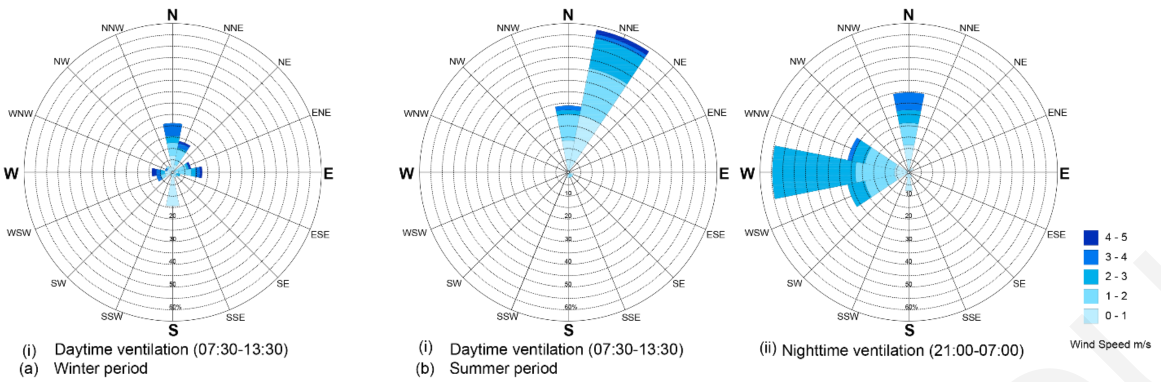



Figure 14.16. Examination of outdoor wind environments for the (a) winter (b) summer period, i.e. 9th of February - 16th of February 2018, and 19th of May - 25th of May 2018 respectively, during daytime, i.e. 07:30-13:30, and night-time, i.e. 21:00-07:00.

In winter, the field data collected from indoors exhibit very low air speed levels in all classrooms, i.e. <0.1m/s. This results from the broad application of the ventilation strategy; i.e. single-sided ventilation, and from the fact that openings face the south, i.e. counter to prevailing winds. During the summer period, the indoor air velocity has an average wind speed of 0.2 m/s during the daytime, while, the air speed during the night is below 0.1 m/s and is attributed to the fact that the openings face south/north.

Table 14.13. Outdoor and indoor recorded values of wind speed during the summer and winter period, i.e. 19th-23th of May 2018 and 09-16th of February 2018.

| | | Wind speed (m/s) | | | | | |
|---|---|---|---|---|---|---|---|
| **Ventilation Strategy** | | **Outdoor** | | | **Indoor** | | |
| | | **max** | **min** | **mean** | **max** | **min** | **mean** |
| **SUMMER (19th-23th May 2018)** | | | | | | | |
| **Case 1** | Day | 4.0 | 0 | 1.5 | 0.3 | 0 | 0.1 |
| | Night | 3.1 | 0 | 1.7 | 0 | 0 | 0 |
| **WINTER (10th-13th February 2018)** | | | | | | | |
| **Case 4** | Day | 4.5 | 0 | 1.6 | 0.1 | 0 | 0 |
| | Night | 4.0 | 0 | 1.1 | 0 | 0 | 0 |

*14.2.2.2. Operative temperature, degree hours, temperature difference ratio and relative humidity*

A review of the indoor and outdoor environmental parameters of a south-oriented classroom, which was naturally ventilated with single-sided ventilation, are presented in Table 14.14 and Table 14.15. More specifically, the tables present the percentage of occupied time within acceptable comfort limits, the CDH and HDH values for both the 80% and 90% acceptability, the temperature difference ratio, the wind speed and relative humidity in the occupied summer period and winter period i.e. 19th – 23th May 2018 and 9th-16th February 2018 respectively.

In winter, the field data collected from indoors exhibit very low air speed levels in all classrooms, i.e. <0.1m/s. This results from the broad application of the ventilation strategy; i.e. single-sided ventilation, and from the fact that openings face the south, i.e. counter to prevailing winds. During the summer period, the indoor air velocity has an average wind speed of 0.2 m/s during the daytime.

Table 14.14 Outdoor and indoor-recorded values, percentage of occupied time within acceptable comfort limits, CDH/HDH and temperature difference ratio during the summer and winter period, i.e. 19th-23th of May 2018 and 10th-13th of February, respectively, between 07:30-13:35.

| Vent. Strategy | Day | Outdoor air temperature (°C) | | | Indoor air temperature (°C) | | | Operative temperature (°C) | | | Fluct. of out. temp (°C) | Fluct. of in. temp. (°C) | Percentage of occupied time within acceptable limits (%) | | CDH / HDH | CDH / HDH | Temperature Difference Ratio | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | max | min | mean | max | min | mean | max | min | mean | mean | mean | 80% | 90% | 80% | 90% | | Aver. |
| **SUMMER (19th-23th May 2018)** | | | | | | | | | | | | | | | | | | |
| **Case 1** | D1 | 37.3 | 25.5 | 32.8 | 33.6 | 30.3 | 31.7 | 33.9 | 30.6 | 32.0 | | | | | 12.1 | 19.1 | 0.3 | |
| | D2 | 36.6 | 25.9 | 32.5 | 34.1 | 30.6 | 32.2 | 34.3 | 30.8 | 32.4 | | | | | 12.6 | 19.6 | 0.2 | |
| | D3 | 36.2 | 24.8 | 31.4 | 33.4 | 30.6 | 33.0 | 33.9 | 30.9 | 32.5 | 10.7 | 4 | 13 | 7 | 11.0 | 18.0 | 0.3 | 0.2 |
| | D4 | 32.7 | 25.2 | 28.6 | 32.9 | 31.2 | 31.8 | 33.1 | 31.6 | 32.1 | | | | | 6.1 | 13.1 | 0.1 | |
| | D5 | 34.7 | 22.8 | 29.5 | 32.5 | 29.0 | 30.7 | 32.6 | 29.7 | 31.1 | | | | | 1.1 | 3.8 | 0.1 | |
| | **Total** | | | | | | | | | | | | | | **42.9** | **73.5** | | |
| **WINTER (10th-13th February 2018)** | | | | | | | | | | | | | | | | | | |
| **Case 4** | D1 | 18.5 | 12.3 | 15.9 | 19.7 | 18.5 | 19.2 | 19.8 | 18.6 | 19.3 | | | | | 10.1 | 17.1 | - | |
| | D2 | 18.7 | 14.9 | 16.7 | 18.5 | 17.6 | 18.0 | 18.5 | 17.7 | 18.1 | | | | | 18.8 | 25.8 | - | |
| | D3 | 16.6 | 10.9 | 14.0 | 19.9 | 16.5 | 18.2 | 19.4 | 16.8 | 18.3 | 5.7 | 2.4 | 0 | 0 | 17.6 | 24.6 | - | - |
| | D4 | 17.9 | 10.9 | 14.3 | 19.8 | 15.7 | 18.2 | 19.5 | 15.9 | 18.3 | | | | | 17.1 | 24.1 | - | |
| | Total | | | | | | | | | | | | | | **63.5** | **91.5** | | |

Table 14.15 Outdoor and indoor recorded values of relative humidity during the summer and winter period, i.e. 19th-23th of May 2018 and 09th-16th of February 2018.

| | **Relative Humidity (%)** | | | | | |
|---|---|---|---|---|---|---|
| **Ventilation Strategy** | **Outdoor** | | | **Indoor** | | |
| | **max** | **min** | **mean** | **max** | **min** | **mean** |
| **SUMMER (19th-23th May 2018)** | | | | | | |
| **Case 1** | 90 | 13 | 37 | 48 | 19 | 32 |
| **WINTER (10th-13th February 2018)** | | | | | | |
| **Case 4** | 96 | 43 | 69 | 73 | 54 | 63 |

*14.2.2.1.1. Period of recording and analysis from the 19th-23th May 2018, Summer period*

The outdoor temperature during summer period varied from 23.6°C to a peak of 38.1°C, with a mean diurnal fluctuation of 12.7°C. During the occupied time, i.e. 07:30-13:30, the outdoor temperature varied from 24.8°C to 37.3°C, with a mean diurnal fluctuation of 10.7°C. The average running mean temperature during the summer period was 27.7°C. Depending on the outdoor conditions, the thermal comfort zone ranged from 24.3-25.3°C to 30.3-31.3 °C for 80% acceptability and from 25.3-26.3°C to 29.3-30.3°C for 90% acceptability. The outdoor relative humidity ranges from 13% to 90% with a mean value of 37%. The acceptable limit of relative humidity ranges from 30% to 70%, but ideally between 40% and 60%. Figure 14.17 shows the assessment of thermal comfort conditions in the selected south-facing classroom with single-sided ventilation during day (Case 1) that represents the most common occupants' behaviour in summer period. The shaded area denotes the periods when the classrooms were occupied. Dash lines indicate the 80% and 90% acceptability limits.

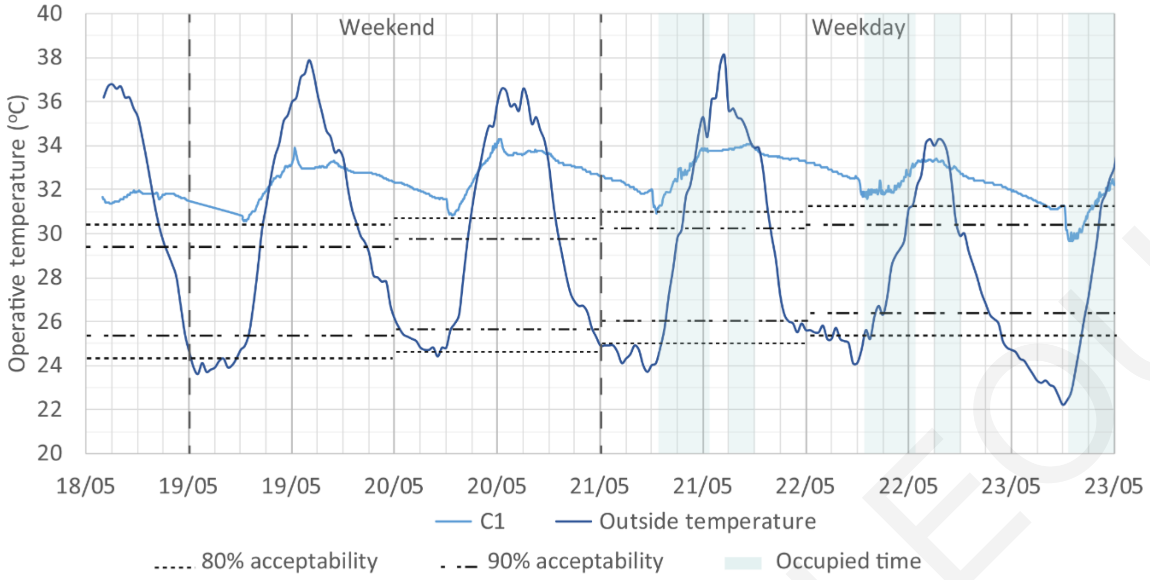



Figure 14.17. Operative temperatures for thermal comfort assessment of the south-oriented classroom under study during the summer period, i.e. 19th of May- 23th of May 2018.

During the application of a single-sided ventilation strategy during the daytime (Case 1), the mean operative temperatures varied from 31.1°C to 32.5°C during the occupied times, i.e. 07:30-13:35, showing a minimum operative temperature of 29.7°C between 07:00-08:00 in the morning, due to the opening of the windows (reduction of 1°C in an hour), while between 13:30-14:30 the maximum temperature was 34.3°C. More specifically, operative temperatures fall within the 80% acceptability limit for 13% of the occupied time and only seven percent within the 90% acceptability limit. Relative humidity ranged from 19% to 48%, with a mean value of 32% (Figure 14.17).

The temperature difference ratio, which defines the cooling performance of passive cooling strategies, is relatively low at 0.2. This means that applied strategies such as single-sided daytime ventilation and a 2m overhang are not enough to cool the building. In terms of the cooling degree-hours, the classroom with single-sided ventilation requires 42.9 CDH for thermal comfort conditions in order to reach the 80% acceptability limits for five days (a week).

*14.2.2.1.2. Period of recording and analysis from the 09th-16th February 2018,Winter period*

The outdoor temperatures **during winter** period varied from 8.5°C to a peak of 18.7°C, with a mean diurnal fluctuation of 7.4°C. During the occupied time, i.e. 07:30-13:35, the outdoor temperature varied from 10.7°C to 18.7°C, with a mean diurnal fluctuation of 5.7°C. The average running mean temperature during the winter period was 14.8°C. The comfort zone was set for 80% and 90% acceptability within classrooms as shown in Fig. 14.18. Depending on the outdoor conditions, the thermal comfort zone ranged from 20.5-20.8°C to 26.5-26.8 °C for 80% acceptability and from 21.5-21.8 °C to 25.5-25.8 °C for 90% acceptability. It would be interesting to note that according to the European Standard EN15251:2007, when the building uses mechanical system for heating, then the thermal comfort zone is set constantly to 20-26°C in Category II, which is very nearly to the adaptive comfort model. However, it should be noted that the technical system is provided only for limited time of the day and only for the heating period; therefore, the building is considered as free running building and the adaptive standards are used. Figure 14.18 shows the assessment of thermal comfort conditions in the selected south facing classroom, which applied ventilation every break-time (Case 4). The shaded area denotes the occupied period of classrooms.

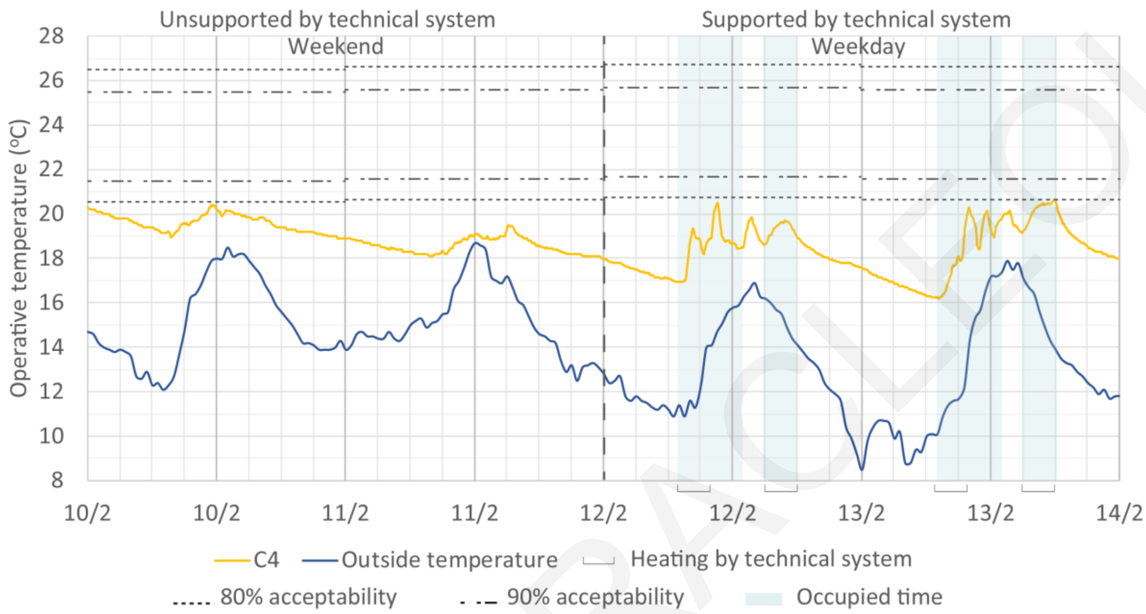



Figure 14.18. Operative temperatures for thermal comfort assessment of south-oriented classroom under study during the winter period, i.e. 09th of February -16th of February 2018.

As observed in Fig. 14.18, the indoor operative temperatures during the winter period, at times when the classrooms are unoccupied, is generally stable as they are not supported by technical systems. During occupied periods where a heating system was operable, the indoor temperature shows higher fluctuations. It is worth mentioning that during the weekend, when no technical heating is provided, all classrooms are below the acceptable thermal comfort limits. In all classrooms, the minimum operative temperature appears between 07:00-8:00 in the morning, while the maximum temperature is recorded between 12:00-13:00 during the weekends and between 10:00-11:00 during the weekdays when the heating system is switched on. In terms of mean relative humidity, it is noted that all recorded values meet the norms.

The mean operative temperatures in the south-oriented classroom (Case 4) varied from 18.6°C to 19.8°C during the occupied time, i.e. 07:30-13:35. It should be stated that the ventilation which occurred during the first break (08:50-09:10) in the classroom (Case 4) did not affect the indoor conditions As observed, operative temperatures are below the acceptability limits for all the occupied and unoccupied times, even with the provision of technical heating (Figure 14.18). The heating degree hours are higher than cooling degree hours and reach 63.5 for four days.

## 14.3. Results of subjective questionnaires about thermal comfort

The findings of the questionnaire answered by the students analysed using Excel and statistical programme Matlab are presented below. The methodology of the qualitative study through questionnaires was described in **Chapter 11.3.** During the questionnaire-survey, the outdoor temperature ranged from 8.5°C to 16.3°C during the winter period, and from 18.6°C to 27.1°C during the summer period, when the classrooms were occupied. It should be noted that the conditions during the questionnaire survey were slightly cooler during the winter, and significantly cooler (approximately 10 degrees lower) during the summer, compared to those recorded during the experimental procedure. Based on the adaptive model incorporated in the EN 15251:2007 [87], the thermal comfort zone during the winter ranges from 20°C to 26°C for 80% acceptability and from 21°C to 25°C for 90% acceptability. The thermal comfort zone during the summer ranges from 23°C to 29°C for 80% acceptability and from 24°C to 28°C for 90% acceptability.

### *14.3.1. Clothing insulation*

In terms of clothing insulation, the questionnaire survey conducted during the teaching periods of the working day reveals that the majority of students have typical uniform clothing. The overall analysis reveals that during the summer period, with outdoor and indoor temperatures ranging from 19°C to 27°C and 24.5°C to 28.5 °C respectively, all students, namely, 100% of the sample, wear trousers and a short-sleeved shirt (~ 0.57 clo). During the winter period, with recorded outdoor and indoor temperatures ranging from 10°C to 16.3°C and 15.5°C to 22.5°C, more than 90% of students wear trousers, a short-sleeved shirt and a long-sleeved sweater (~ 1 clo), while a proportion of 10% wear an additional jacket (~ 1.2 clo). It should be noted that correlation is demonstrated between clothing insulation (~ 1.2 clo) and outdoor air temperature (10 -16.3°C) during the working hours of the winter period.

### *14.3.2. Thermal comfort responses*

The overall analysis of the comfort survey on thermal sensations during the winter period shows that the occupants felt neutral or slightly cool with mean values of thermal sensation of -0.07. Small variations in responses are shown between genders. A slightly higher trend is reported in the boys' responses. Specifically, 10.1% of boys felt warm or hot compared to the 2.5% of girls (Figure 14.19). A significant correlation is observed between the time of the day and thermal sensation, as occupants felt neutral during midday hours when the temperature rose. Specifically, 40.3% of students who felt neutral, filled out the questionnaire at midday (11:30-13:30) when the outdoor temperature was above 15°C, 31.4% during late morning (10:00-11:30) and 27.7% during morning time (07:30-10:00). In addition, there is an important connection between cold thermal sensation and the morning period ($r=0.03$, $p<0.05$).

The mean distribution of thermal sensation reported during the summer period shows that the occupants felt mostly slightly warm, with mean values of thermal sensation of 0.92, affected by the

33.9% that felt slightly warm, by the 17.3% that felt warm and by the 9.1% that felt hot. The relationship between time of day and thermal sensation is also evident during the summer period. Specifically, half of the students (49.6%) felt neutral during the morning period when the outdoor temperature was below 22°C, while at midday, the percentage dropped to 19.8%. Another strong connection is noticed between midday and warm thermal sensation ($r=0.17$, $p<0.05$).

### *14.3.3. Thermal preference responses*

A significant correlation was found between thermal preferences and thermal sensation ($p<0.05$). The responses from the survey reveal that during winter, 40% of the respondents preferred no change to the thermal environment, 38.5% preferred slightly warmer or much warmer and 20.7% cooler or much cooler. Specifically, the mean thermal preference is 0.22, specifically stating preference for no change or slightly warmer environments. The effect of gender is also shown in thermal preferences votes. Specifically, 47% of girls preferred a slightly warmer or much warmer environment compared to the 30% of boys, while 15% of girls preferred slightly cooler or much cooler environment compared to 27% of boys with the same preference (Figure 14.19). A significant correlation was found between thermal preferences and air movement, as the students who preferred slightly warmer or much warmer environments, preferred a bit less and much less air movement ($r=0.19$, $p<0.05$), and at the same time the students who preferred a slightly cooler environment, preferred a bit more air movement ($r=0.39$, $p<0.05$). A strong link is noticed between the preference for higher air movement and cooler thermal preferences ($r= 0.90$, $p<0.05$).

During the summer period, 24.4% of the respondents preferred no change to the thermal environment, however most students, i.e. 73.9%, preferred slightly cooler or much cooler environments and only 1.6% preferred a slightly warmer environment. Specifically, the mean thermal preference is -0.94 for slightly cooler environments (Figure 14.19). A significant relationship is noticed between the preference for higher air movement and thermal preferences ($r=0.38$, $p<0.05$). The 65% of respondents who felt slightly warm, warm or hot, preferred a bit more or much more air movement; yet there was a large percentage that did not need any change to air movement, i.e. 35%.

### *14.3.4. Thermal acceptability responses*

During the field study, the respondents showed a high acceptability for the immediate thermal environment, with 76% of students feeling comfortable during winter and 71% during summer (Figure 14.19). It is worth mentioning that a significant correlation is found between thermal acceptability and clothing insulation ($r=0.58$, $p<0.05$). Specifically, more than 90% of respondents who wore a sweater and more than 9% who wore a jacket feel comfortable during winter. A relationship is also identified between thermal acceptability and air movement. Specifically, 51% of students who felt comfortable did not want any change in air movement ($r=0.39$, $p<0.05$).

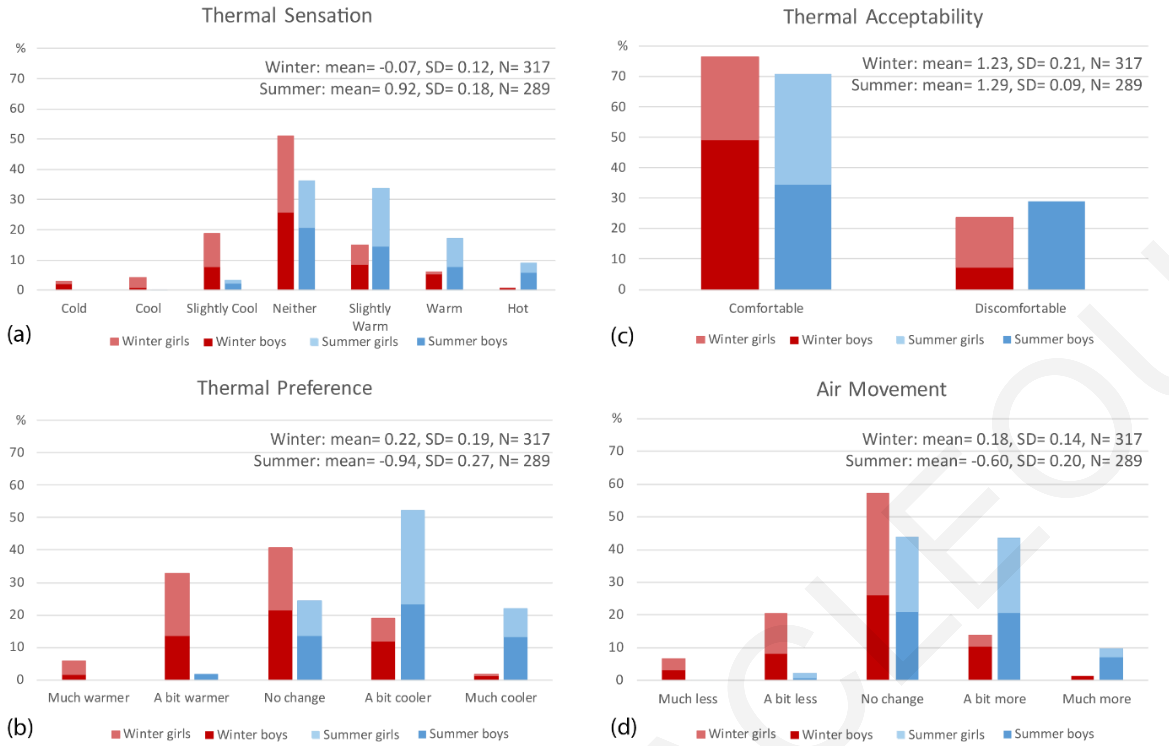



Figure 14.19. Percentage distribution of (a) thermal sensation, (b) thermal preference, (c) thermal acceptability and (d) air movement preference votes during summer and winter period.

### *14.3.5. Activity responses*

In terms of activity, the students were asked to state their activity during the last 30 minutes. The analysis revealed that during the winter period, more students were walking or running (34.4%) compared to the summer period (24.4%). However, most of them were doing sedentary activities, i.e. sitting on standing. Specifically, 65.4% and 75.6% of the students were sitting or standing during winter and summer period respectively.  The more rigorous work during the winter period can be expressed as a means of increasing their thermal sensation. The analysis also revealed that the highest percentage of students, (50.8%), who felt slightly warm or warm during the winter had been walking or running during the last 30 minutes, while the rest were standing or sitting. A significant correlation was found between gender and activity; specifically, it was found that more girls than boys had been running in thec last 30 minutes ($r=-0.11$, $p<0.05$).

It has been observed that by drinking either hot or cold beverages, occupants can increase their own personal thermal comfort [485]. A percentage of approximately 65% of students highlighted that they had consumed a cold drink during the summer period, while 20% stated that they had consumed hot drinks or snacks during the winter period. Moreover, 50% of students that felt either cold or cool had consumed hot drinks or a hot snack in the last 30 minutes. However, only 14.2% of students felt comfortable after having their drinks or snacks.

### *14.3.6. Indoor Environmental Control Votes*

Regarding the control of the indoor environmental conditions, students could open or close the windows and curtains to regulate the indoor environmental parameters. Based on the respondents' answers and field observation, windows during the winter period were opened near to midday when the temperature is higher compared to the morning hours, while during the summer period windows were opened during the entire day. Window opening patterns relate both to indoor and outdoor temperature. In terms of curtain operation, it was observed that they were closed or partly closed throughout the day in each season, in order to avoid distraction problems and glare issues (Figure 14.20).

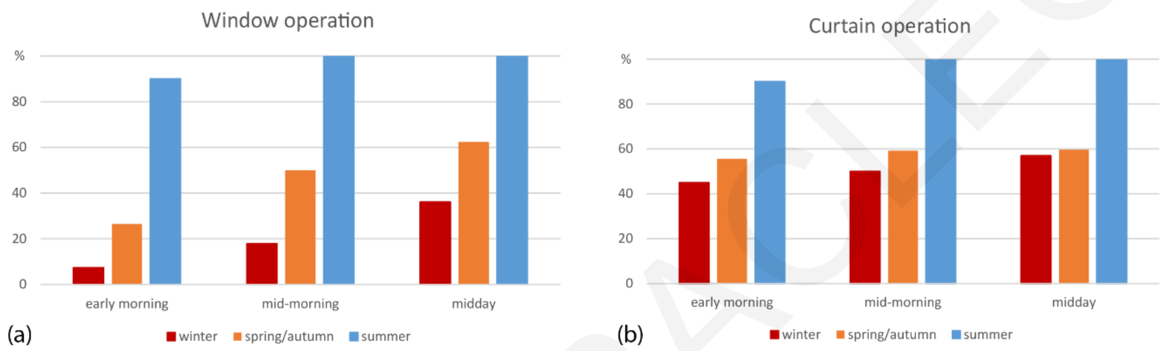



Figure 14.20. Percentage of votes for window and curtain operation during the year.

### *14.3.7. Comfort Temperatures*

Despite the fact that based on the adaptive thermal comfort model (EN 15251:2007), the neutral temperature during the winter period was between 20°C and 26°C, the majority of students, i.e. 30.7%, felt neutral at 21-22.5°C, 27.1% at 15.5-17°C, 21.3% at 19°C-19.5°C, and 19.8% at 17.5°C (Figure 14.21a). This shows high levels of thermal tolerance, as more than 68% of students feel neutral in temperatures below the acceptable thermal comfort zone. Regarding the students that felt cool or cold, as it was expected, 69.6% of students had this feeling in temperatures below the adaptive comfort zones, while 30.4% of students felt cold or cool in a range of temperatures of 21-22.5°C. It is interesting to mention that the majority of students (47.8%) that felt warm or hot, filled the questionnaires when the indoor air temperature ranged between 15.5-17.5°C, showing the effect of their position near the heating panels, where temperatures are higher (Figure 14.21a).

During the summer period, based on the adaptive comfort model, the comfort zone ranged from 23°C to 29°C for an 80% acceptability limit. The majority of students (50.9%), felt neutral at a range of temperatures of 26-27°C, 34.8% at temperatures of 25-26°C; 9.9% at temperatures of 24.5-25°C and only 4.4% at temperatures of 27.5-28.5°C (Figure 14.21b). This observation shows that students are more vulnerable to temperatures above 27°C, even though the comfort zone extends up to 29°C according to the adaptive model. It is also worth noting that most occupants (82.7%) who felt warm or hot, filled the questionnaire when the indoor temperature was between 25.5-27°C (Figure 14.21b).

Figure 14.21 shows the correlation between indoor air temperature and students' percentage votes for each thermal sensation and the regression line between indoor air temperature and thermal comfort votes for winter and summer. Due to the fact that questionnaires were filled in different classrooms with different orientations with variation in temperature across classrooms, an average indoor temperature is employed for each period which serves to correlate with comfort conditions. The students' percentage votes of cold and cool thermal sensation and warm and hot thermal sensation were grouped as they represent the extreme limits (Figure 14.21 a and b). Concerning the relationship between indoor air temperature and proportion of comfort, it should be mentioned that slightly cool [-1], neutral [0] and slightly warm [+1] votes are also grouped in order to be calculated as comfortable conditions (Figure 14.21 (c) and (d)). As shown in Figure 14.21 (c) the proportion of students who feel comfortable during winter increases as the temperature increases. However, a high percentage of votes at lower temperatures of 16.5 °C shows students' tolerance of low temperatures which may be related to their ability to keep within a comfort zone by wearing warm clothes. On the other hand, during the summer period, according to subjective questionnaires, the number of students who feel comfortable increases when the temperature reaches 26 - 26.5°C with polynomial fit lines indicating lower percentage below and above these values.

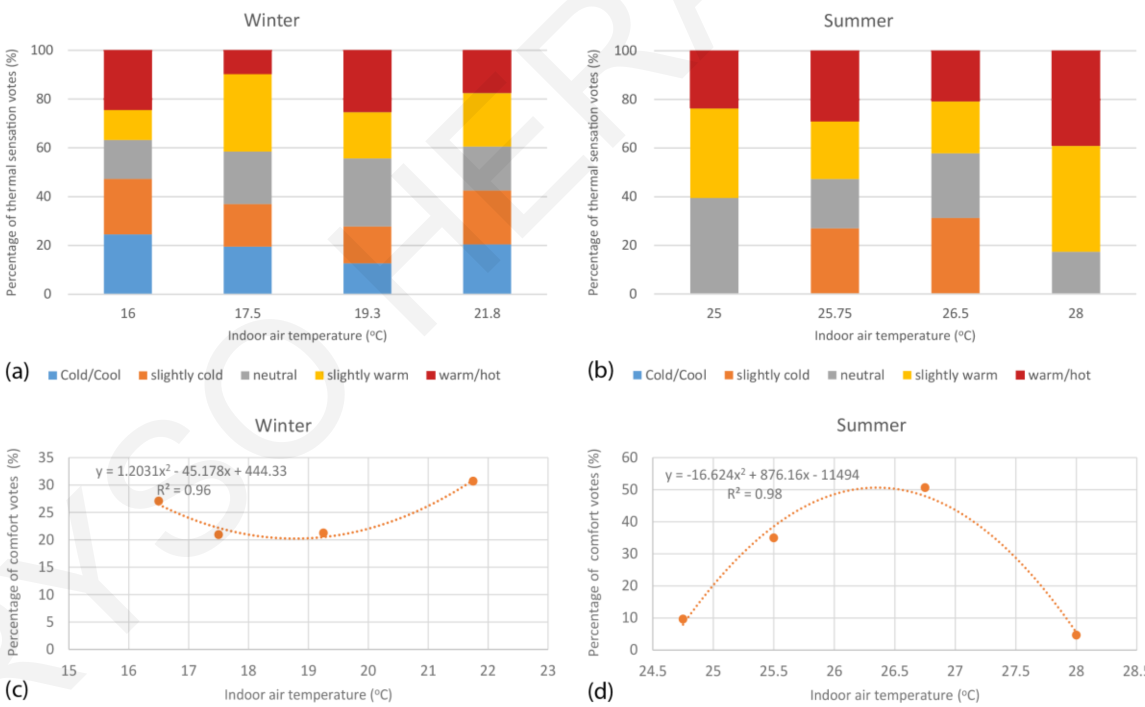



Figure 14.21. Correlation between indoor air temperature and students' percentage votes for each thermal sensation and the regression line between indoor air temperature and thermal comfort votes [-1, 0, +1] for winter and summer.

## 14.4. Results of dynamic simulation

### *14.4.1. Environmental performance of existing educational buildings under different climatic scenarios without the support of technical systems*

The assessment of the resilience of school buildings provides valuable information in the effort to understand the necessity of producing measures of energy retrofitting, so as to contribute to policies and interventions that will lead to more energy-efficient, retrofitting solutions. The study employed a calibrated model with built in dynamic thermal simulations using Integrated Environmental Solutions-Virtual Environment (IES-VE). The methodology of quantitative study through software simulation was described in **Chapter 11.4.**

Results were assessed by adaptive comfort standards and heating and cooling degree hours in TMY, 2050 and 2090 under the scenario A1B. Measure combinations which diminish heating demand, and overheating risk, may be applied to adjust to the most prominent needs of the space at certain times. The analysis was performed during the hours of occupation between 07:30-13:30 for both ground floor classrooms and first floor classrooms in south orientation. It is worth mentioning that the analysis was undertaken only during the period when educational buildings are in operation, i.e., September to June, excluding Christmas and Easter holidays.

The educational building in question exhibits higher needs for heating compared to cooling throughout the operational period. The classroom on the first floor requires slightly higher energy compared to the classroom on the ground floor, as it has higher exposure to outside environmental conditions. Specifically, throughout the whole academic year, the heating degree hours of the classroom of the first floor was 3187.6, while the cooling degree hours was 90.7. Throughout the whole academic year, the heating degree hours of the classroom of the ground floor was 3487.1, while the cooling degree hours was 30.8.

The results regarding the future climatic scenarios of 2050 and 2090 show an increase in cooling demands and a decrease in heating demands compared to the TMY, due to the increment of outdoor air temperature. Specifically, in 2050, the heating degree hours of the reference building reduced by about 17% and the cooling degree hours increase by 50-80% (first and ground floor level respectively) leading to total energy reduction of about 15% compared to the TMY. This is attributed to the fact that the school buildings are closed during summer time, avoiding the highest effect of overheating, and due to the warmer winter in the future climate conditions which in turn leads to higher percentage of hours within the thermal comfort zone. In 2090, the heating degree hours of the reference building reduce by 31% and the cooling degree hours increase by 135-213% (first and ground floor level respectively) leading to a total degree-hours reduction of 26-29% compared to the TMY (Table 14.16).

Figure 14.22 shows in a bar chart the monthly heating and cooling degree hours of the reference building during the occupied hours throughout the entire academic year, for the three climatic conditions, i.e. TMY, 2050, and 2090. It should be noted that July, August, Christmas and Easter holidays are excluded from the analysis as the school buildings are not operated that periods. Based on the results of adaptive comfort standards:

- During the current climatic conditions, only May required both heating and cooling with 89.4% represents heating in the specific month;
- During 2050, again only May required both heating and cooling with 56.8% represents heating and 43.2% represents cooling.
- During 2090, May and October required both heating and cooling. For May, 5.8% represents heating and the rest 94.2% represents cooling; while for October, 99.4% represents heating and 0.6% represents cooling.

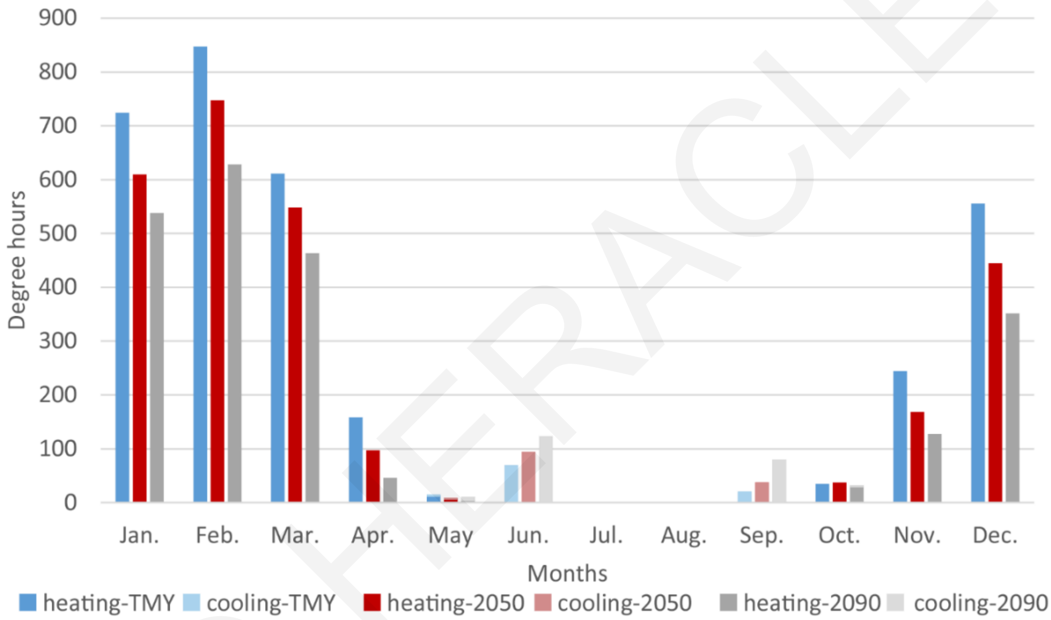



Figure 14.22. Monthly degree hours for heating and cooling for TMY, 2050, 2090 of the reference building during the occupied hours, throughout the entire academic year.

In order to identify the performance of educational building throughout the entire year, including holidays and summer period, Figure 14.23 was created showing the monthly heating and cooling degree hours of the reference building during the occupied hours for the three climatic conditions, i.e. TMY, 2050, and 2090. As observed, July and August, as expected, are the warmest months of the year confirming the necessity of schools to not operating during these months.

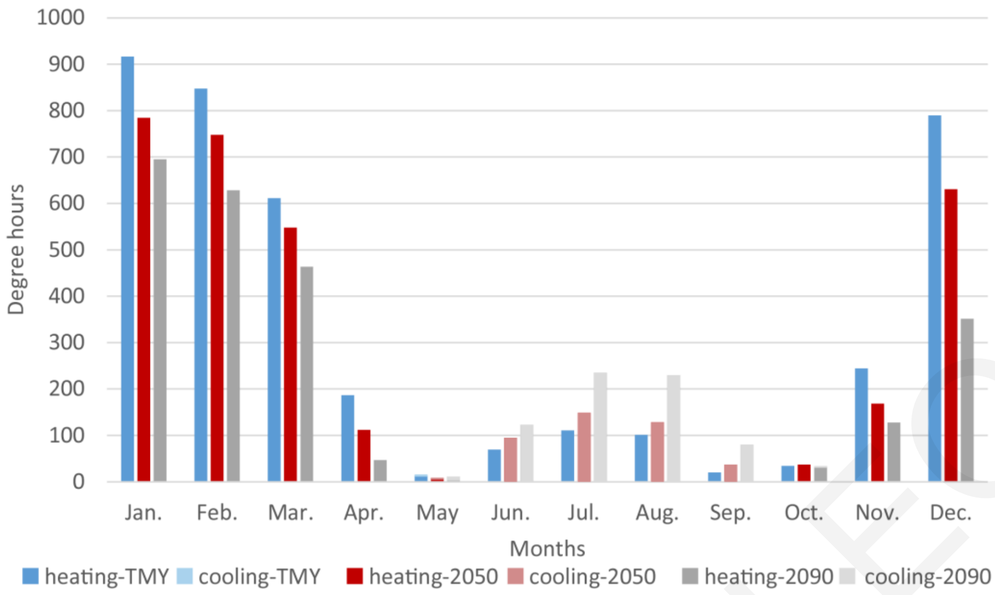



Figure 14.23. Monthly degree hours for heating and cooling for TMY, 2050, 2090 of the reference building during the occupied hours, throughout the entire year.

Figure 14.24 shows the monthly degree hours of January and June and the annual degree hours of the reference building during the occupied hours for the TMY (first dot), 2050 (second dot) and 2090 (third dot). As expected, the degree hours for heating in January decrease over the years showing a linear relationship between the degree hours and the monthly mean outdoor temperature with $R^2$ value higher than 0.99. The correlation between the degree hours for cooling and the mean outdoor temperature is also strong, with the $R^2$ value higher than 0.99, showing an increase of cooling demand as years progress. The annual degree hours exhibit an overall decrease in the future indicating a similar correlation with outdoor air temperature ($R^2$= 0.99) due to the substantially higher contribution of heating to energy demands. It is interesting to mention that during the summer, an increase of outdoor monthly mean air temperature by 0.5°C causes an increase in degree hours of about 15.8 (i.e., 22.8% increase), while in winter an increase of outdoor monthly mean air temperature by 0.5°C results in a decrease of about 44.2 degree hours (i.e., 6.1% decrease). The effect of the increase in temperature during the summer is more adverse as the type of building and its function and operation leave it exposed to the worse conditions of midday. An increase in outdoor annual mean air temperature of 0.5°C will cause a decrease of the annual degree hours to about 206.3 (i.e., 6.3% decrease).

Table 14.16. Predicted heating and cooling degree hours in TMY and percentage of change of 2050s and 2090s in south classrooms during hours of occupation (07:30-13:35) using the 80% acceptability limit.

| | Occupied hours (07:30-13:35) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | First floor classroom | | | | | | Ground floor classroom | | | | | |
| | Degree hours | | | Percentage change (%) | | | Degree hours | | | Percentage change (%) | | |
| | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total |
| **TMY** | 3187.6 | 90.7 | 3278.3 | - | - | - | 3487.1 | 30.8 | 3517.9 | - | - | - |
| **2050** | 2658.1 | 135.4 | 2793.5 | -16.6 | 49.2 | -14.8 | 2921.6 | 55.7 | 2977.3 | -16.5 | 80.8 | -15.4 |
| **2090** | 2187.5 | 213.4 | 2400.9 | -31.4 | 135.3 | -26.8 | 2388.6 | 96.5 | 2485.2 | -31.5 | 213.3 | -29.4 |

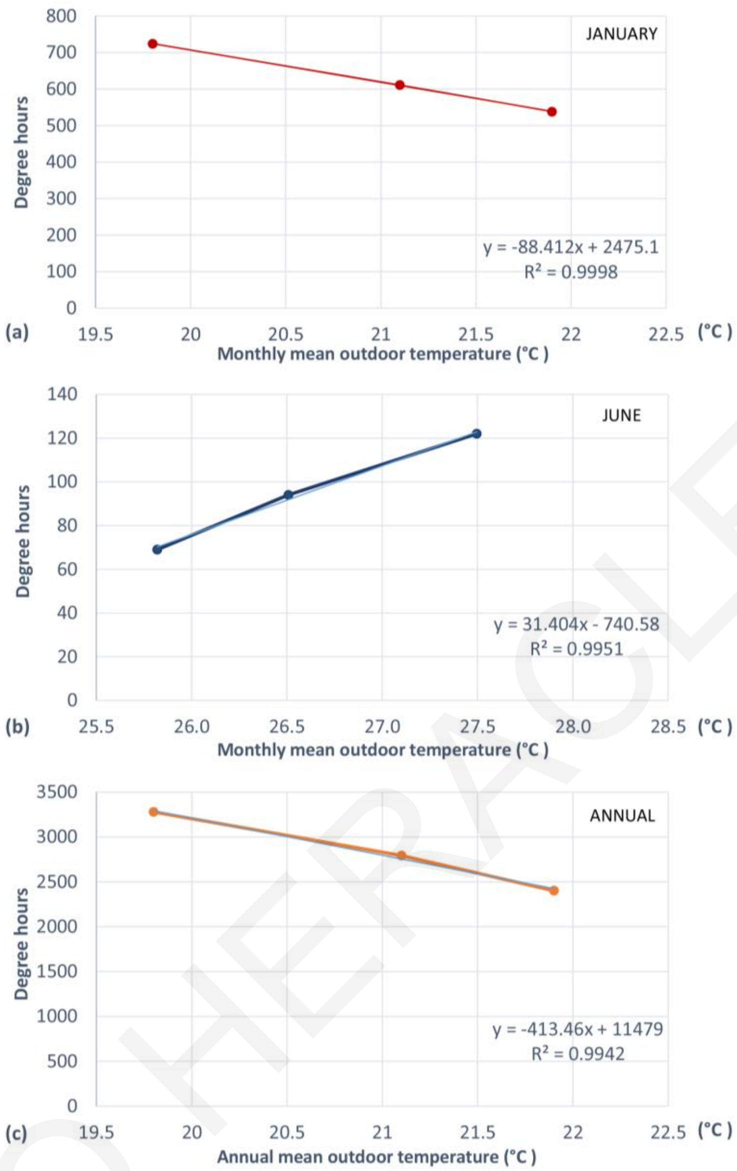



Figure 14.24. (a) Heating degree hours versus monthly mean outdoor air temperature in January (winter), (b) Cooling degree hours versus monthly mean outdoor air temperature in June (summer) and (c) annual degree hours versus annual mean outdoor air temperature, for the three periods (TMY-first dot in series, 2050-second dot in series, and 2090-third dot in series) for a south classroom on the first floor during the occupied period. For each line, the left dot represents the TMY, the middle dot represent the 2050 and the right dot represents the 2090.

Figure 14.25 shows the monthly degree hours for all months and the annual degree hours of the reference building during the occupied hours for the TMY (first dot in series), 2050 (second dot in series) and 2090 (third dot in series). July and August were presented only for information; while they should be excluded due to the non-operation of the educational buildings during summer period. Moreover, it should be noted that October during heating period presented an anomaly during the TMY, reaching higher temperatures compared to 2050 in some days, thus leading to a lower correlation between monthly mean temperatures and heating degree hours.

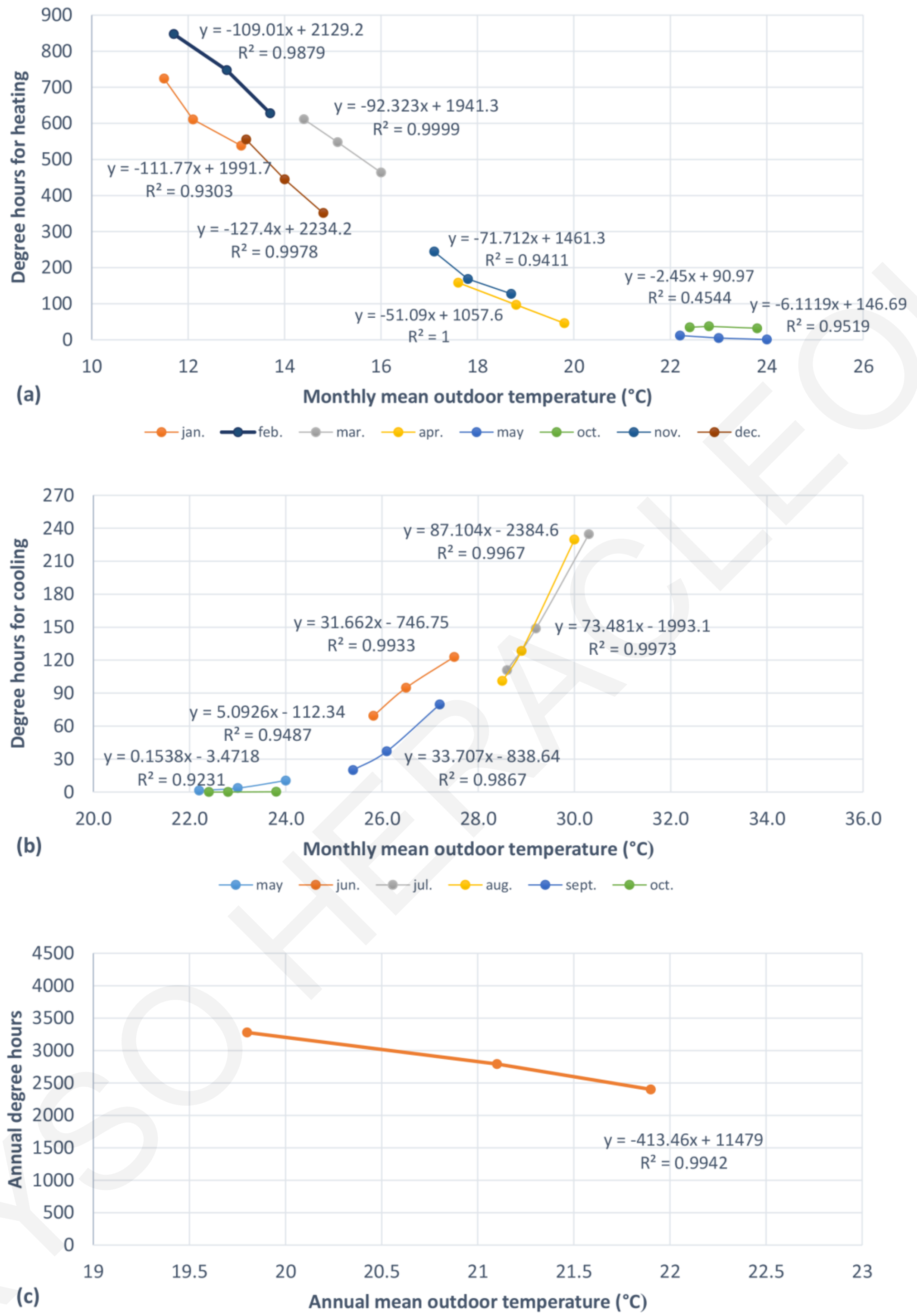



Figure 14.25. (a) Heating degree hours versus monthly mean outdoor air temperature for cold months (b) Cooling degree hours versus monthly mean outdoor air temperature for warm month and (c) annual degree hours versus annual mean outdoor air temperature, for the three periods (TMY-first dot in series, 2050-second dot in series, and 2090-third dot in series) for a south classroom on the first floor during the occupied hours. For each line, the left dot represents the TMY, the middle dot represents the 2050 and the right dot represents the 2090.

### *14.4.2. Overheating risk*

As overheating is becoming a key problem in building design, the present study aims to investigate how educational buildings will perform in view of rising temperatures in the future and examine the implications on both energy performance and people's health. For the assessment of the thermal comfort vulnerability of schools in Cyprus, dynamic thermal simulations were undertaken using the Integrated Environmental Solutions-Virtual Environment (IES-VE). The European Standard EN 15251:2007 [87] is used to assess the thermal comfort in naturally ventilated buildings using the adaptive comfort approach. Moreover, this work looks at the overheating criteria from CIBSE TM 52 [455] and tests them on a typical model (overheating criteria are described in **Chapter 11.4.7.1.3**). Table 14.17 presents the results of the three criteria in the middle class of the first floor in different orientations for the current typical meteorological year, for 2050, and 2090 for the reference classroom. Criterion 2 presents the weighted exceedance and criterion 3 shows the exceedance in hours.

#### *14.4.2.1. Typical Meteorological Year*

For the present TMY (Typical Meteorological Year) (Table 14.17), the base case of the south and north-oriented classroom, i.e. the classroom with the largest windows facing south and north respectively and the clerestories facing the opposite side which provides daytime ventilation only between 07:30-12:50, passed all the criteria (1-3). Specifically, the numbers of hours in the non-typical heating season when operative temperature exceeded $T_{\max}$ is exactly 3% of the occupied time while indoor temperature never exceeded 4K compared to $T_{max}$. However, east and west-oriented classrooms failed to pass criterion 1 by 1%; while they passed criterion 2 and 3. South- oriented classrooms exhibit the lowest tendency for overheating due to lower solar gains because of existing overhangs.

#### *14.4.2.2. Future climatic conditions of 2050s and 2090s*

Looking at the future climatic scenarios of 2050 and 2090, there is a clear tendency for severe overheating. Classrooms in all four orientations in the reference scenario failed all the criteria and were unable to cope with overheating predictions solely relying on the current passive cooling strategies (Table 14.17). In 2050, for the daytime ventilation strategy (reference scenario), more than half of the occupied period is predicted to suffer from overheating, while in 2090, more than 70% of the time. Moreover, a large amount of hours exceed the limit of maximum absolute value of 4K which indicates that adaptive actions will be insufficient to restore personal comfort and that the vast majority of occupants will complain about excessive heat.

Table 14.17. TM52 criteria for the base case for different classroom orientations in line with climatic predictions.

| Day time ventilation only (Reference) | | | | | | |
|---|---|---|---|---|---|---|
| | TMY | | 2050 | | 2090 | |
| **South** | | | | | | |
| **C1** | Pass | 3% | Fail | 53% | Fail | 68% |
| **C2** | Pass | 0.03 | Fail | 8.8 | Fail | 19.1 |
| **C3** | Pass | 0 | Fail | 42 | Fail | 192 |
| **North** | | | | | | |
| **C1** | Pass | 3% | Fail | 55% | Fail | 69% |
| **C2** | Pass | 0.31 | Fail | 9.4 | Fail | 19.9 |
| **C3** | Pass | 0 | Fail | 42 | Fail | 203 |
| **East** | | | | | | |
| **C1** | Fail | 4% | Fail | 64% | Fail | 74% |
| **C2** | Pass | 0.4 | Fail | 11.4 | Fail | 22.0 |
| **C3** | Pass | 0 | Fail | 51 | Fail | 244 |
| **West** | | | | | | |
| **C1** | Fail | 4% | Fail | 62% | Fail | 72% |
| **C2** | Pass | 0.4 | Fail | 13.0 | Fail | 23.9 |
| **C3** | Pass | 0 | Fail | 53 | Fail | 248 |

### *14.4.3. Energy Performance of existing educational buildings and life cycle cost analysis*

The assessment of the energy performance and life cycle cost of school buildings, provides valuable information in the effort to understand the necessity of producing measures of energy retrofitting, so as to contribute to policies and interventions that will lead to more energy-efficient retrofitting solutions. The study employed a calibrated model with built-in dynamic thermal simulations using Integrated Environmental Solutions-Virtual Environment (IES-VE). The methodology supporting this kind of quantitative study through software simulation was described in **Chapter 11.4.2 and Chapter 11.4.7.2.**

Results were assessed according to the energy demands for heating and cooling in the current climatic conditions. The analysis was performed during the hours of occupation i.e., 07:30-13:30, for both ground floor classrooms and first floor classrooms with south orientation. It is worth mentioning that the analysis was undertaken only during the period when the educational buildings are in operation, i.e., September to June, excluding Christmas and Easter holidays.

The educational building in question exhibits higher needs for heating compared to cooling throughout the operational period. The classroom on the first floor requires slightly higher energy compared to the classroom on the ground floor, as it has higher exposure to outside environmental conditions through the roof. Specifically, the heating loads represent the 73% and 79% of the total energy loads for the classroom on the first and ground floor, respectively, and the cooling loads represent the 27% and 21% of the total energy loads for the classroom on the first and ground floor respectively. Throughout the whole academic year, the primary energy for heating in the classroom of the first floor was 88% of total primary energy and was 67.9 kWh/m$^2$/yr; while for cooling represented the 12% and was 12.4 kWh/m$^2$/yr. Throughout the whole academic year, the primary energy for heating in the classroom of the ground floor represented the 91% of the total primary energy and was 68.2 kWh/m$^2$/yr; while for cooling represented the 9% and was 6.9 kWh/m$^2$/yr.

The lifecycle cost for 30 years for the classroom on the first and ground floor is €20,347 and €20,081 respectively. For life cycle cost calculation, please see Appendix G.

Table 14.18 summarizes the performance of the south-facing classroom on the first and ground floor in the existing conditions including energy loads, final energy consumption, primary energy consumption, $CO_2$ emissions, and life cycle cost.

Table 14.18. Performance analysis of the reference building.

| Reference | First floor | Ground floor |
|---|---|---|
| **Annual Heating Load (kWh/m$^2$/yr)** | 56.8 | 57.1 |
| **Annual Cooling Load (kWh/m$^2$/yr)** | 20.8 | 15.3 |
| **Annual Heating Consumption (kWh/m$^2$/yr)** | 61.7 | 62.0 |
| **Annual Cooling Consumption (kWh/m$^2$/yr)** | 3.5 | 2.5 |
| **Total Annual Consumption (kWh/m$^2$/yr)** | 65.2 | 64.6 |
| **Annual Primary Energy for Heating (kWh/m$^2$/yr)** | 67.9 | 68.2 |
| **Annual Primary Energy for Cooling (kWh/m$^2$/yr)** | 9.4 | 6.9 |
| **Total Annual Primary Energy (kWh/m$^2$/yr)** | 77.2 | 75.1 |
| **$CO_2$ Emissions for Heating (kg$CO_2$)** | 18.1 | 18.1 |
| **$CO_2$ Emissions for Cooling (kg$CO_2$)** | 7.4 | 12.9 |
| **Total $CO_2$ Emissions (kg$CO_2$)** | 25.5 | 23.6 |
| **Life Cycle Cost (€)** | 20,347 | 20,081 |

## 14.5. Synopsis and Discussion

### *14.5.1. Synopsis regarding field measurements and subjective questionnaires about thermal comfort*

The study includes a comparative analysis of indoor conditions, via the evaluation of air temperatures of classrooms in different orientations and operative temperature in south-oriented classrooms. The statistical analysis of hourly values of temperature shows a significant correlation between the studied classrooms during the weekdays and the weekend ($p<0.05$) (Figure 14.17 and 14.18). The results also suggest a significant correlation between the mean temperature of the classrooms and the outdoor temperature ($p<0.05$). Significant variations between the temperature values of the classrooms are shown between occupied and unoccupied periods during both the winter and summer period.

Classrooms record temperatures lower or higher than acceptable comfort limits in both winter and summer. The results are in agreement with de Giuli et al. [159] and Dorizas et al. [188] stating that during warm period, the indoor environment is not satisfactory for the occupants. The prevailing occupant behaviour of the single-sided ventilation strategy fails to ensure thermal comfort conditions during the summer; while during winter, it can reduce operative temperature by up to 1°C in 20 minutes, when the outdoor temperature is below 15°C. However, a study by the authors described in

**Chapter 16.2** and **Chapter 16.3** shows that continuous ventilation is necessary during occupied time for ensuring a high indoor air quality. Overall, all the above-mentioned findings disclose the necessity to improve the building structures of schools, including aspects of thermal insulation and airtightness.

The results of this survey show that when it comes to sensation, more than 70% of the students experienced a range of thermal comfort from slightly cool to slightly warm, both in winter and summer. Additionally, the preferred thermal condition stated was "no change" to the internal environment during the winter, and "slightly cooler" during the summer. The evaluation of thermal comfort conditions shows that students have high levels of tolerance regarding thermal conditions, as demonstrated by the high levels of comfort even at the thermal states of TS= ±2 or TS= ±3 both in winter and summer.

Concerning the correlation of temperatures with thermal sensation, it was observed that students' neutral temperature is lower than the one calculated by the adaptive comfort model during both winter and summer. Specifically, almost 50% of students felt neutral when the temperature ranged between 17.5-19.5°C during winter period and when the temperature ranged between 26-27°C during summer period.

In general, students felt that their thermal environment was hotter than the temperatures forecast by the data measured. This is in line with the study carried out by Dorizas et al. [186] in nine schools in Greece, reaching to the same conclusion. The study also reveals that students are more vulnerable to higher temperatures and adaptive limits undervalue thermal sensation and forecast temperatures above the comfort zone. This is in line with studies performed by Singh et al. [27], Lee et al. [486], Teli et al. [340] and Hwang et al. [181] who state that children are more vulnerable to high temperatures and favours a colder thermal condition. The researches in question also reveal that students are doubly vulnerable to temperature shifts in the summer rather than in winter.

Moreover, this research shows that boys have a slightly warmer sensation than girls and therefore prefer higher air movement in both winter and summer (Figure 14.19). This is in line with the study undertaken by Karjalainen [100] who found that there are significant differences in thermal comfort between genders, and specifically females express more dissatisfaction than males especially in cooler conditions. It should also be noted that a significant correlation is found between thermal acceptability and clothing insulation. Because students can adapt to the environment by wearing a long-sleeved sweater and an additional jacket, they can tolerate lower indoor temperatures when they fall below acceptable limits. Respectively, during summer time, students change their attire to lighter clothing in order to adapt to higher outdoor temperature conditions. This is in line with the study performed by Humphreys [122], who found different comfort temperatures for different clothing.

The findings of this study have to be viewed in light of some limitations deriving from the experimental character of the research. Firstly, although adaptive comfort standards presuppose that the buildings will not be technically supported by systems, educational buildings in Cyprus provide heating for limited period of time during winter affecting the thermal performance of classrooms. To minimize the negative effect of this limitation, an additional analysis was undertaken during weekends without the operation of any heating system. Secondly, the variation in the occupancy levels of classrooms, and the lack of uninterrupted occupancy, because the students move around to other laboratory or physical education classrooms during the day, may influence the recorded indoor condition data. Finally, the subjective questionnaires were filled by students during specific days of each season. The recording of data during different days and periods of the year, with more variations in temperatures will allow a more detailed investigation of students' thermal sensation.

### *14.5.2. Synopsis of dynamic simulation*

The key aspect of the chapter includes an assessment and analysis of the impact of climate change on thermal comfort and the energy performance of educational buildings, and brings to the fore how essential it is to timely plan retrofitting actions to mitigate the predicted effect. The case study building has been modelled and calibrated using dynamic simulation software (IES-VE), in order to determine the potential impact of climate change (2050, 2090) under the A1B scenario. As described in **Chapter 11.4.3**, future scenarios show that the air temperature will rise both during winter and summer, with an average annual increase of 0.7°C in 2050 and 1.7°C in 2090. The highest increase appears during the spring period (Figure 11.11) with an average increase of 1.2°C and 2.3°C in April for 2050 and 2090 respectively. Additionally, the mean minimum temperature will rise by about 1.5°C and 3°C for 2050 and 2090 respectively, leading to hotter nights. The impact of climate change is expected to further aggravate the overheating risk and thus the discomfort of occupants if no action is taken. This is in line with findings in other studies [4], [7]–[10], [333], [337], [487], [488] that suggest that energy demand associated with cooling will increase in the future. On the other hand, heating demand is expected to be reduced and, as this is the predominant source of in-use energy in educational buildings, it will result in an overall reduction in annual demand.

The proportion of 3% for cooling seems to be negligible compared to the 97% of heating in the TMY, while in the future it will increase to 5% and 9% in 2050 and 2090 respectively. Specifically, in 2050, the heating degree hours for the reference building reduces by 16-17% and the cooling degree hours increase by 50-80% (first and ground floor level respectively), leading to total energy reduction of 17-15% compared to the TMY. In 2090, the heating degree hours of the reference building reduce by 31% and the cooling degree hours increase by 135-213% leading to a total degree hours reduction of 27-29% compared to the TMY. The results are in line with the study of Asimakopoulos et al. [333] who noted an increase of cooling demand up to 248% by 2100.

With regards to the overheating risk, the research highlights that typical teaching spaces in Cyprus, oriented to the north and south, overcome the overheating risk in the present climatic conditions; however, classrooms oriented to the east and west, experience temperatures that exceed the CIBSE limits for 4% of the occupied hours.

Concerning the energy performance of the classrooms, the study shows that the heating loads represent the 73% and 79% of the total energy loads of the classrooms on the first and ground floor respectively, and the cooling loads represent the 27% and 21% of the total energy loads of the classrooms on the first and ground floor respectively. The total primary energy was 77.2 kWh/m$^2$/yr and 75.1 kWh/m$^2$/yr for classrooms on the first and ground floor with a life cycle cost of €20,347 and €20,081 respectively over 30 years.

# Chapter 15. Assessment of the thermal comfort and energy performance of educational buildings under current and future climatic scenarios, Part B: retrofit approaches and their implications

## 15.1. Introduction

This chapter is organized into two main subdivisions to present the analysis of assessment of retrofit approaches and their implications on thermal and energy performance under current and future climatic scenarios and evaluate their cost-effectiveness. The first section of this chapter describes the results from the experimental procedure on-site for proper operation of windows for each season in order to identify at what extent natural ventilation can affect the performance in the specific climatic conditions and in the specific typology of building. The second, reports the results of the dynamic simulation of different retrofitting measures under different climatic conditions, as well as their cost-effectiveness with again a special assessment of the proper operation of windows on overheating risk. Finally, a synopsis and discussion are provided.

## 15.2. Results of experimental procedure on-site for proper operation of windows

The critical inquiry of the study looks at whether it is possible to reach a thermal comfort level without the use of technical equipment for cooling during the summer period and for fresh air during the winter period. The methodology of the on-site experimental procedure for proper operation of windows was described in **Chapter 11.2.2**. Classrooms within the educational premises of Southern Europe have diachronically employed natural ventilation as an essential cooling strategy during the summer months. The results of this study give insight into how natural ventilation may be best employed while, it promotes the educational character of the school and directly enhances the role of environmental education, as it fosters an understanding of energy and environmental sensitivity and awareness to future generations. Schools form encouraging instances of public buildings and energy performance, as they stand out as examples to the students themselves who can actually see the enhancements occurring in classrooms. It should be noted that similar building arrangements of linear disposition such as classrooms, connected with semi-open corridors like the ones mentioned in this study are commonly found in other countries of the Eastern Mediterranean region that share similar climatic conditions with Cyprus and thus the results of the current study can be applied in a wider sample of buildings.

### *15.2.1. Adaptive comfort models*

A review of the indoor and outdoor environmental parameters in classrooms which were naturally ventilated are presented in Table 15.1 and Table 15.2. More specifically the tables present the percentage of occupied time within acceptable comfort limits, the CDH and HDH values for both the 80% and 90% acceptability, the temperature difference ratio, the wind speed and relative humidity in the occupied summer period and winter period i.e. 19th – 23th of May 2018 and 09th-16th of February 2018 respectively.

Table 15.1. Outdoor and indoor recorded values, percentage of occupied time within acceptable comfort limits, CDH and HDH and temperature difference ratio during the summer and winter period, i.e. 19th-23th of May 2018 and 09th -16th of February respectively between 07:30-13:35.

| Vent. Strategy | Day | Outdoor air temperature (°C) | | | Indoor air temperature (°C) | | | Operative temperature (°C) | | | Fluct. of out. temp (°C) | Fluct. of in. temp. (°C) | Percentage of occupied time within acceptable limits (%) | | CDH / HDH | CDH / HDH | Temperature Difference Ratio | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | max | min | mean | max | min | mean | max | min | mean | mean | mean | 80% | 90% | 80% | 90% | | Aver. |
| **SUMMER (19th-23th May 2018)** | | | | | | | | | | | | | | | | | | |
| **Case 1** | D1 | 37.3 | 25.5 | 32.8 | 33.6 | 30.3 | 31.7 | 33.9 | 30.6 | 32.0 | | | | | 12.1 | 19.1 | 0.3 | |
| | D2 | 36.6 | 25.9 | 32.5 | 34.1 | 30.6 | 32.2 | 34.3 | 30.8 | 32.4 | | | | | 12.6 | 19.6 | 0.2 | |
| | D3 | 36.2 | 24.8 | 31.4 | 33.4 | 30.6 | 33.0 | 33.9 | 30.9 | 32.5 | 10.7 | 4 | 13 | 7 | 11.0 | 18.0 | 0.3 | 0.2 |
| | D4 | 32.7 | 25.2 | 28.6 | 32.9 | 31.2 | 31.8 | 33.1 | 31.6 | 32.1 | | | | | 6.1 | 13.1 | 0.1 | |
| | D5 | 34.7 | 22.8 | 29.5 | 32.5 | 29.0 | 30.7 | 32.6 | 29.7 | 31.1 | | | | | 1.1 | 3.8 | 0.1 | |
| | **Total** | | | | | | | | | | | | | | **42.9** | **73.5** | | |
| **Case 2** | D1 | 37.3 | 25.5 | 32.8 | 33.5 | 29.2 | 31.3 | 33.7 | 29.4 | 31.4 | | | | | 9.5 | 15.7 | 0.3 | |
| | D2 | 36.6 | 25.9 | 32.5 | 33.7 | 29.4 | 31.6 | 34.0 | 29.5 | 31.8 | | | | | 9.7 | 15.5 | 0.2 | |
| | D3 | 36.2 | 24.8 | 31.4 | 33.4 | 29.2 | 31.3 | 33.9 | 29.4 | 31.8 | 10.7 | 5 | 39 | 12 | 8.0 | 13.5 | 0.3 | 0.2 |
| | D4 | 32.7 | 25.2 | 28.6 | 32.5 | 29.5 | 30.9 | 32.6 | 30.1 | 31.4 | | | | | 2.3 | 8.1 | 0.6 | |
| | D5 | 34.7 | 22.8 | 29.5 | 32.2 | 27.8 | 30.2 | 32.5 | 28.3 | 30.7 | | | | | 2.2 | 6.0 | 0.2 | |
| | **Total** | | | | | | | | | | | | | | **31.7** | **58.8** | | |
| **Case 3** | D1 | 37.3 | 25.5 | 32.8 | 32.2 | 29.0 | 30.7 | 32.4 | 29.2 | 30.9 | | | | | 5.9 | 12.0 | 0.4 | |
| | D2 | 36.6 | 25.9 | 32.5 | 32.5 | 29.4 | 31.3 | 32.8 | 29.7 | 31.5 | | | | | 6.9 | 13.2 | 0.4 | |
| | D3 | 36.2 | 24.8 | 31.4 | 32.6 | 29.3 | 31.2 | 33.3 | 29.5 | 31.7 | 10.7 | 4.4 | 33 | 11 | 6.4 | 12.5 | 0.5 | 0.3 |
| | D4 | 32.7 | 25.2 | 28.6 | 32.2 | 30.1 | 31.1 | 32.4 | 30.4 | 31.5 | | | | | 2.4 | 8.7 | 0.2 | |
| | D5 | 34.7 | 22.8 | 29.5 | 31.7 | 27.9 | 30.3 | 31.8 | 28.3 | 30.6 | | | | | 0.8 | 4.4 | 0.2 | |
| | **Total** | | | | | | | | | | | | | | **22.3** | **50.8** | | |
| **Case 4** | D1 | 37.3 | 25.5 | 32.8 | 34.1 | 29.8 | 31.8 | 34.1 | 30.0 | 31.8 | | | | | 11.5 | 18.5 | 0.3 | |
| | D2 | 36.6 | 25.9 | 32.5 | 34.3 | 30.7 | 32.4 | 34.3 | 30.8 | 32.5 | 10.7 | 3.7 | 19 | 7 | 12.9 | 19.9 | 0.2 | 0.2 |
| | D3 | 36.2 | 24.8 | 31.4 | 34.1 | 30.7 | 32.2 | 35.5 | 31.5 | 32.6 | | | | | 11.3 | 18.3 | 0.3 | |
| | D4 | 32.7 | 25.2 | 28.6 | 32.8 | 30.4 | 31.3 | 34.3 | 31.1 | 32.5 | | | | | 2.6 | 9.5 | 0.1 | |
| | D5 | 34.7 | 22.8 | 29.5 | 32.8 | 29.2 | 31.0 | 32.5 | 30.8 | 31.6 | | | | | 2.7 | 6.7 | 0.1 | |
| | **Total** | | | | | | | | | | | | | | **41.1** | **73.0** | | |
| **WINTER (10th-13th February 2018)** | | | | | | | | | | | | | | | | | | |
| **Case 1** | D1 | 18.5 | 12.3 | 15.9 | 21.0 | 19.3 | 20.3 | 21.1 | 19.6 | 20.4 | | | | | 2.6 | 9.2 | - | |
| | D2 | 18.7 | 14.9 | 16.7 | 19.4 | 18.4 | 18.9 | 19.4 | 18.5 | 19.0 | | | | | 12.3 | 19.3 | - | |
| | D3 | 16.6 | 10.9 | 14.0 | 22.2 | 17.1 | 20.2 | 21.8 | 17.5 | 20.3 | 5.7 | 2.9 | 34 | 18 | 5.6 | 10.8 | - | - |
| | D4 | 17.9 | 10.9 | 14.3 | 22.7 | 18.9 | 21.6 | 22.5 | 20.4 | 21.7 | | | | | 0.3 | 1.7 | - | |
| | **Total** | | | | | | | | | | | | | | **20.8** | **41.0** | | |
| **Case 2** | D1 | 18.5 | 12.3 | 15.9 | 20.7 | 19.2 | 20.1 | 20.8 | 19.4 | 20.2 | | | | | 3.5 | 10.4 | - | |
| | D2 | 18.7 | 14.9 | 16.7 | 19.4 | 18.7 | 19.1 | 19.4 | 18.7 | 19.1 | | | | | 11.7 | 18.7 | - | |
| | D3 | 16.6 | 10.9 | 14.0 | 21.9 | 17.4 | 19.9 | 21.8 | 17.7 | 20.0 | 5.7 | 2.8 | 25 | 4 | 6.8 | 12.6 | - | - |
| | D4 | 17.9 | 10.9 | 14.3 | 21.6 | 17.2 | 20.4 | 21.4 | 17.9 | 20.6 | | | | | 2.9 | 8.0 | - | |
| | **Total** | | | | | | | | | | | | | | **24.9** | **49.7** | | |
| **Case 3** | D1 | 18.5 | 12.3 | 15.9 | 20.2 | 19.2 | 19.8 | 20.2 | 19.3 | 19.9 | | | | | 5.4 | 12.9 | - | |
| | D2 | 18.7 | 14.9 | 16.7 | 19.1 | 18.4 | 18.7 | 19.1 | 18.4 | 18.8 | | | | | 14.3 | 21.3 | - | |
| | D3 | 16.6 | 10.9 | 14.0 | 21.8 | 17.2 | 19.8 | 21.3 | 17.5 | 19.8 | 5.7 | 2.7 | 12 | 3 | 7.6 | 13.8 | - | - |
| | D4 | 17.9 | 10.9 | 14.3 | 21.7 | 17.2 | 19.6 | 21.2 | 19.4 | 20.1 | | | | | 1.1 | 4.4 | - | |
| | **Total** | | | | | | | | | | | | | | **28.4** | **52.4** | | |
| **Case 4** | D1 | 18.5 | 12.3 | 15.9 | 19.7 | 18.5 | 19.2 | 19.8 | 18.6 | 19.3 | | | | | 10.1 | 17.1 | - | |
| | D2 | 18.7 | 14.9 | 16.7 | 18.5 | 17.6 | 18.0 | 18.5 | 17.7 | 18.1 | | | | | 18.8 | 25.8 | - | |
| | D3 | 16.6 | 10.9 | 14.0 | 19.9 | 16.5 | 18.2 | 19.4 | 16.8 | 18.3 | 5.7 | 2.4 | 0 | 0 | 17.6 | 24.6 | - | - |
| | D4 | 17.9 | 10.9 | 14.3 | 19.8 | 15.7 | 18.2 | 19.5 | 15.9 | 18.3 | | | | | 17.1 | 24.1 | - | |
| | **Total** | | | | | | | | | | | | | | **63.5** | **91.5** | | |

Table 15.2. Outdoor and indoor recorded values of wind speed and relative humidity during the summer and winter period, i.e. 19th -23th of May 2018 and 09th -16th of February 2018.

| Ventilation Strategy | | Wind speed (m/s) Outdoor max | min | mean | Indoor max | min | mean | Relative Humidity (%) Outdoor max | min | mean | Indoor max | min | mean |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **SUMMER (19th-23th May 2018)** | | | | | | | | | | | | | |
| **Case 1** | Day | 4.0 | 0 | 1.5 | 0.3 | 0 | 0.1 | 90 | 13 | 37 | 48 | 19 | 32 |
| | Night | 3.1 | 0 | 1.7 | 0 | 0 | 0 | | | | | | |
| **Case 2** | Day | 4.0 | 0 | 1.5 | 0.7 | 0 | 0.1 | 90 | 13 | 37 | 52 | 19 | 32 |
| | Night | 3.1 | 0 | 1.7 | 0 | 0 | 0 | | | | | | |
| **Case 3** | Day | 4.0 | 0 | 1.5 | 0.1 | 0.5 | 0.1 | 90 | 13 | 37 | 51 | 21 | 34 |
| | Night | 3.1 | 0 | 1.7 | 0.1 | 0.1 | 0 | | | | | | |
| **Case 4** | Day | 4.0 | 0 | 1.5 | 0.1 | 0.6 | 0 | 90 | 13 | 37 | 48 | 18 | 30 |
| | Night | 3.1 | 0 | 1.7 | 0 | 0 | 0 | | | | | | |
| **WINTER (10th-13th February 2018)** | | | | | | | | | | | | | |
| **Case 1** | Day | 4.5 | 0 | 1.6 | 0 | 0 | 0 | 96 | 43 | 69 | 64 | 47 | 57 |
| | Night | 4.0 | 0 | 1.1 | 0 | 0 | 0 | | | | | | |
| **Case 2** | Day | 4.5 | 0 | 1.6 | 0.1 | 0 | 0 | 96 | 43 | 69 | 65 | 48 | 58 |
| | Night | 4.0 | 0 | 1.1 | 0 | 0 | 0 | | | | | | |
| **Case 3** | Day | 4.5 | 0 | 1.6 | 0.1 | 0 | 0 | 96 | 43 | 69 | 67 | 47 | 57 |
| **Case 4** | Day | 4.5 | 0 | 1.6 | 0.1 | 0 | 0 | | | | | | |
| | Night | 4.0 | 0 | 1.1 | 0 | 0 | 0 | 96 | 43 | 69 | 73 | 54 | 63 |

### *15.2.1.1. Summer period, 19th-23th of May 2018*

The outdoor temperature during the summer period varied from 23.6°C to a peak of 38.1°C, with a mean diurnal fluctuation of 12.7°C. During the occupied time, i.e. 07:30-13:30, the outdoor temperature varied from 24.8°C to 37.3°C, with a mean diurnal fluctuation of 10.7°C. The average running mean temperature during the summer period was 27.7°C. Depending on the outdoor conditions, the thermal comfort zone ranged from 24.3-25.3°C to 30.3-31.3 °C for 80% acceptability and from 25.3-26.3°C to 29.3-30.3°C for 90% acceptability based on the adaptive comfort model incorporated in the EN15251:2007. The outdoor relative humidity ranges from 13% to 90% with a mean value of 37%. The acceptable limit of relative humidity ranges from 30% to 70%, but ideally between 40% and 60%. Figure 15.1 shows the assessment of thermal comfort conditions in the four selected south-facing classrooms with different ventilation strategies, i.e. single-sided ventilation during day (Case 1), cross-ventilation during day and night (Case 2), cross-ventilation only during night (Case 3) and cross-ventilation during day (Case 4). The shaded area denotes the periods when the classrooms were occupied. Dash lines indicate the 80% and 90% acceptability limits.

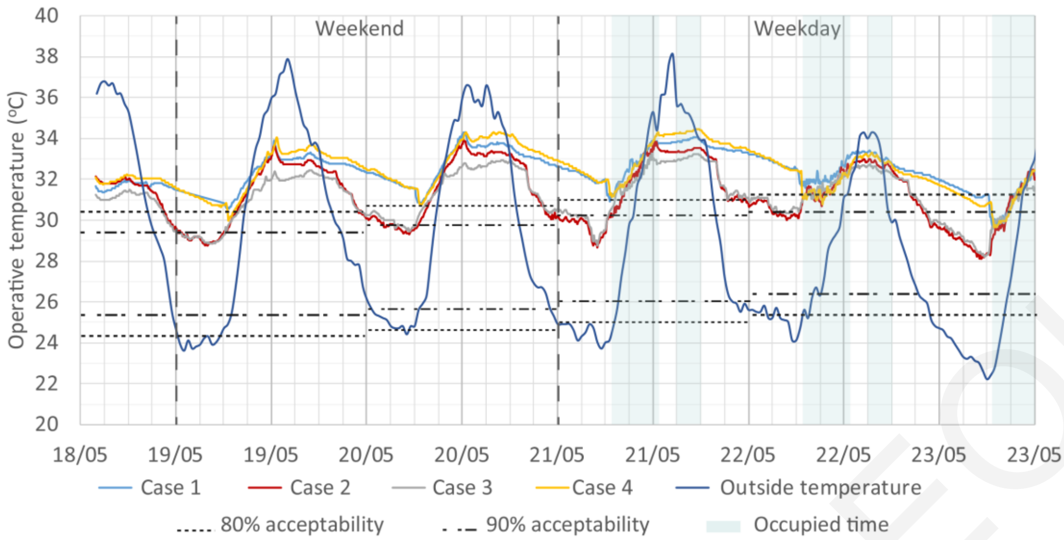



Figure 15.1. Operative temperatures for the thermal comfort assessment of natural ventilation strategies under study (Case 1: single-sided ventilation during day, Case 2: cross-ventilation during day and night, Case 3: cross-ventilation only during night and Case 4: cross-ventilation during day) during the summer period, i.e. 19th May- 23th of May 2018.

During the application of a **single-sided ventilation strategy** during the daytime (Case 1), the mean operative temperatures varied from 31.1°C to 32.5°C during the occupied times, i.e. 07:30-13:35, showing a minimum operative temperature of 29.7°C between 07:00-08:00 in the morning, due to the opening of the windows (reduction of 1°C in an hour), while between 13:30-14:30 the maximum temperature was 34.3°C. More specifically, operative temperatures fall within the 80% acceptability limit for 13% of the occupied time and only seven percent within the 90% acceptability limit. Relative humidity ranged from 19% to 48%, with a mean value of 32%.

When **cross-ventilation is applied during daytime** (Case 4), the percentage of time when operative temperatures fall within the 80% acceptability limit increases to 19% of the occupied time. Moreover, it was observed that the classroom employing cross-ventilation is more effective until midday, as it exhibits slightly lower air temperatures of 0.2°C average as opposed to classrooms with single-sided ventilation. However, after midday, Case 4 recorded higher temperatures compared to Case 1 and this may be attributed to the fact that Case 4 has more surfaces exposed to the outdoor environment. The mean operative temperatures varied from 31.6°C to 32.6°C during the occupied time, with the minimum operative temperature of 30°C between 07:00-08:00 in the morning due to the opening of windows (reduction of 1°C in half hour), while between 13:00-14:00, the maximum temperature was 35.5°C. It is worth mentioning that although a small decrease was observed in the operative temperatures when the windows were closed at 13:35 letting the solar gains out, an increase in temperature occurred from 15:00 to 18:00, as the heat energy absorbed by the building envelope was released into the internal environment. Relative humidity ranged from 18% to 47.4%, with a mean value of 30.8%. It seems that the higher the ventilation during daytime, the lower the relative humidity, leading to dryer conditions.

During the application of the **cross-ventilation strategy during the day and night** (Case 2), nocturnal air temperatures closer followed the patterns of outdoor temperatures when compared to the other two strategies (Case 1 and 4). The day following the application of night ventilation, Case 2 presented lower temperatures compared to Case 1 and Case 4. In terms of the adaptive comfort model, Case 2 shows the best performance during the occupied time. Specifically, the mean diurnal operative temperatures fall within the 80% acceptability limit 39% of occupied time, and 12% of the time they fall within the 90% acceptability limit. The mean operative temperatures varied from 30.7°C to 31.8°C during the occupied time. Case 2 showed the minimum operative temperature of 28.1°C between 05:00-06:00 in the morning due to night ventilation, i.e. 1.6°C lower than the classroom without night cooling, while the maximum temperature of 34°C was reached between 13:30-14:30. During night ventilation, heat that remained in the indoor space as well as heat absorbed in the building envelope was released, reducing the peak operative temperatures the next day and thus ensuring better thermal conditions. The application of cross-ventilation during the daytime allows the indoor daily temperatures to correspond to outdoor air temperatures. Relative humidity ranged from 18.9% to 51.5%, with a mean value of 32.4%.

During the application of **night-time cross-ventilation** (Case 3), nocturnal air temperatures follow the patterns of outdoor temperatures similar to Case 2, i.e. cross-ventilation during the day and night. During the following day of the application of night ventilation, Case 3 maintained lower temperatures compared to Case 1 and Case 4, similarly to Case 2. However, when the windows closed at 07:00 in the morning, the indoor temperatures slightly increased compared to Case 2 where cross-ventilation was applied during the day. This increase lasted until 08:00-08:30 in the morning; after that, the indoor air temperatures remained at lower levels compared to Case 2, as Case 3 remained closed, blocking the solar gains. It is worth mentioning that during the weekend, the difference between the indoor daytime temperatures of Case 3 and Case 2 is bigger compared to the indoor daytime temperatures on weekdays (Figure 15.1). This is attributed to the fact that during the week, the classroom that was closed and occupied (Case 3) presenting elevated indoor temperatures due to the heat produced by the occupants. In terms of the adaptive comfort model, Case 3 shows similar performances as Case 2 during the occupied time. Specifically, the mean diurnal operative temperatures fall within the 80% and 90% acceptability limits for 33% and 11% of occupied time respectively. The slightly worse performance compared to Case 2 can be attributed to the closed windows during the effective cooling, which lasts until 8:00 in the morning, as well as the additional heat produced by occupants during the teaching hours, which could not be released to the outdoor environment. The mean operative temperatures varied from 30.6°C to 31.7°C during the occupied time (similarly to Case 2). Case 3 recorded the minimum operative temperature of 28.2°C between 05:00-06:00 in the morning due to night ventilation, while the maximum temperature of 33°C was recorded between 17:00-18:00. This is the lowest peak temperature observed in all the classrooms under study. Relative humidity ranged from 21.2% to 51.4%, with a mean value of 34.6%. It is worth mentioning that this classroom shows higher relative humidity values due to the space abstaining from ventilation.

The mean relative humidity in all cases barely meets the limit of 30%; however, some midday summer days show relative humidity below the limit, creating an unpleasant dry environment.

The analysis also showed correlation between the hourly operative temperature of the classrooms and the outdoor temperature ($p<0.05$). As observed, the classrooms that applied night ventilation, i.e. Case 2 and Case 3, show the strongest correlation ($r=0.87$ and $r=0.78$ respectively) compared to classrooms that applied daytime ventilation, i.e. Case 1 and Case 4 ($r=0.5$) (Table 15.3).

*15.2.1.2.Winter period, 10^th^ of February- 14^th^ of February 2018*

The outdoor temperatures during the winter period varied from 8.5°C to a peak of 18.7°C, with a mean diurnal fluctuation of 7.4°C. During the occupied time, i.e. 07:30-13:35, the outdoor temperature varied from 10.7°C to 18.7°C, with a mean diurnal fluctuation of 5.7°C. The average running mean temperature during the winter period was 14.8°C. The comfort zone was set for 80% and 90% acceptability within classrooms as shown in Figure 15.2 based on the adaptive comfort model incorporated in the EN15251:2007. Depending on the outdoor conditions, the thermal comfort zone ranged from 20.5-20.8°C to 26.5-26.8 °C for 80% acceptability and from 21.5-21.8 °C to 25.5-25.8 °C for 90% acceptability. It would be interesting to note that according to the European Standard EN15251:2007, when the building uses mechanical system for heating, then the thermal comfort zone is set constantly to 20-26°C in Category II, which is very nearly to the adaptive comfort model. However, it should be noted that due to the fact that educational buildings in supported by technical system only during winter period and for limited time of the day, the building is therefore considered as free running building. Figure 15.2 shows the assessment of thermal comfort conditions in the four selected south facing classrooms with different window operation patterns, i.e. no ventilation (Case 1); ventilation during the last five-minute break (Case 2); ventilation during the last two breaks (Case 3) and ventilation every break-time (Case 4). The shaded area denotes the occupied period of classrooms.

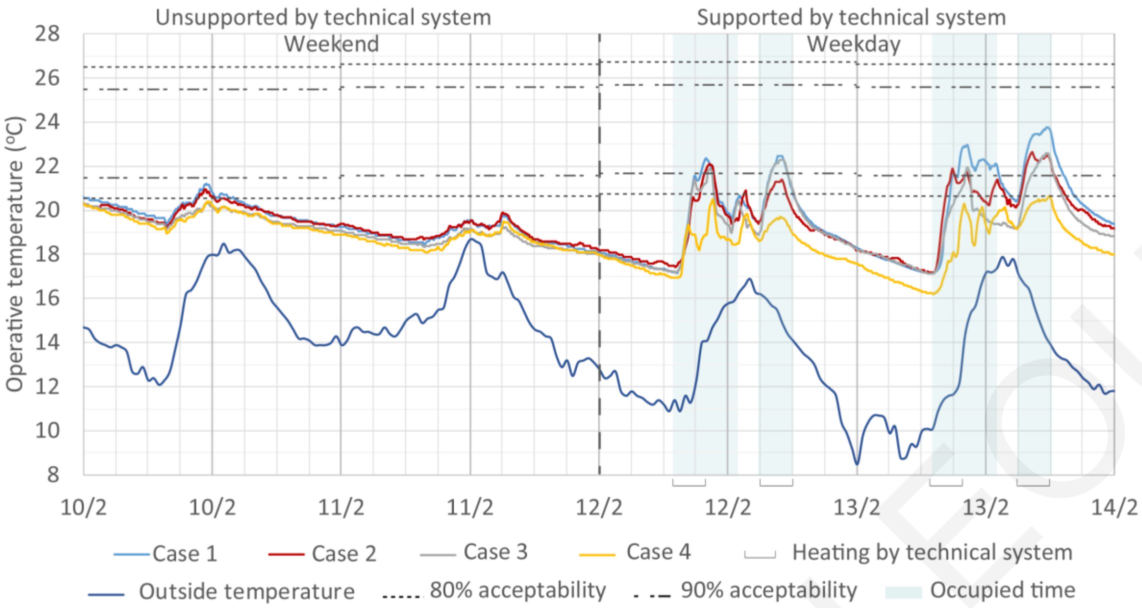



Figure 15.2. Operative temperatures for the thermal comfort assessment of window opening patterns under study (Case 1: no ventilation, Case 2: ventilation during the last five-minute break, Case 3: ventilation during the last two breaks and ventilation every break-time (Case 4). during winter period, i.e. 10th of February- 14th of February 2018.

As observed in Figure 15.2, the indoor operative temperatures during the winter period, at times when the classrooms are unoccupied, is generally stable as they are unsupported by technical systems. During occupied periods where a heating system was provided, as expected the indoor temperature shows higher fluctuations. The correlation between indoor temperatures and outdoor temperatures shows that Case 4 has the strongest correlation (r4=0.742) compared to other classrooms (r1=0.526, r2=0.593, r3= 0.515), possibly due to the higher number of surfaces exposed to the outdoor environment (Table 15.1). This correlation is more visible during occupied times where technical heating is provided. It is worth mentioning that during the weekend, when no technical heating is provided, all classrooms are below the acceptable thermal comfort limits. In all classrooms, the minimum operative temperature appears between 07:00-8:00 in the morning, while the maximum temperature is recorded between 12:00-13:00. In terms of mean relative humidity, it is noted that all recorded values meet the norms.

One of four classrooms (Case 1) remained **without any natural ventilation** during the winter period, for reference purposes. Case 1 showed the highest indoor temperatures compared to other cases due to lesser heat losses through ventilation with mean operative temperatures varied from 19°C to 21.7°C during the occupied time, i.e. 07:30-13:35. More specifically, operative temperatures fall within the 80% acceptability limit for 34% of occupied time and only 18% of occupied time within the 90% acceptability limit, even with the provision of technical heating. It is worth mentioning that a mean temperature reduction of 1.4°C was observed by switching off the heating system for an hour.

With regards to the experimental procedure of different window opening patterns, classrooms Case 2 and Case 3 show similar behaviour. The 20-minute ventilation during the second break (10:30-10:50) in Case 3, reduced the operative temperature by 1.0°C when the outdoor temperature was below 15°C. The five-minute ventilation which occurred in the last break (12:10-12:15) did not affect the internal conditions in both classrooms. The mean operative temperatures of Case 2 and Case 3 varied from 19.1°C to 20.6°C and from 18.8°C to 20.1°C respectively during occupied times, i.e. 07:30-13:35. For classrooms Case 2 and Case 3, operative temperatures fall within the 80% acceptability limit for 25% and 12% of occupied time respectively, while the percentages are slightly lower for 90% of the acceptability limit, i.e. 4% and 3% of occupied time respectively.

Case 4 exhibits the lowest performance concerning thermal comfort conditions. However, the study showed that ventilation is required during every break time to reduce the concentration of $CO_2$ in order to maintain the indoor air quality (**Chapter 12.2.3** and **Chapter 16.2.2**). It is worth mentioning that during the weekend, Case 4 shows similar behaviour to other classrooms. During the week, with the provision of technical heating and a steeper drop of outdoor temperatures, Case 4 shows lower temperatures compared to Case 1 by 2.2°C, and by 1.2°C and 1.5°C compared to Case 2 and Case 3 respectively. It should be stated that the ventilation which occurred during the first break (08:50-09:10) in Case 4 did not affect the indoor conditions. The mean operative temperatures varied from 18.6°C to 19.8°C during the occupied time, i.e. 07:30-13:35. As noticed, operative temperatures are below the acceptability limits for all the occupied and unoccupied times, even with the provision of technical heating.

Table 15.3. Correlation between the recorded internal temperature and outdoor temperature.

| | **Pearson correlation** | |
|---|---|---|
| **Ventilation strategy** | **Winter** | **Summer** |
| **Case 1** | 0.526* | 0.500* |
| **Case 2** | 0.593* | 0.871* |
| **Case 3** | 0.515* | 0.785* |
| **Case 4** | 0.742* | 0.500* |
| *Correlation is significant at the 0.05 level (2-tailed) | | |

### *15.2.2. Temperature Difference Ratio*

Temperature Difference Ratio defines the cooling performance of passive cooling strategies and is shown in Table 15.1. As a first remark, the TDR index does not show significant variations between classrooms. The highest cooling performance efficiency is presented in the case without any ventilation during the daytime and the provision of night ventilation (Case 3), as this case shows the highest TDR value, i.e. an average of 0.3 compared to the various other ventilation strategies which were examined, showing an average TDR value of 0.2. This is attributed mainly to the lowest peak indoor air temperatures, which are on average 3.7°C lower than the peak outdoor temperatures, as a result of less heat gains during the daytime. Case 2 applies both night ventilation and cross daytime ventilation, enabling the daily indoor temperatures to come closer to the outdoor environment. The cooling efficiency of both single-sided and cross daytime ventilation is lower than the abovementioned strategies since the windows are closed during the period that outdoor temperatures are reduced, i.e. night time hours.

### *15.2.3. Heating and Cooling Degree-Hours*

The cooling (CDH) and heating degree-hours (HDH) are used as a gauge to assess how well each of the various ventilation strategies and window opening patterns under study perform in terms of heating and cooling. According to Table 15.1, during the summer period, the lowest cooling degree-hours is recorded in the classroom with no daytime ventilation and the application of night ventilation (Case 3). For the five days under study, Case 3 requires a total of 22.3 CDH for the 80% acceptability limit. Slightly higher cooling degree-hours values are demonstrated during the application of the cross-ventilation strategy during the day and night (Case 2). Specifically, 31.7 CDH in total is required to maintain indoor conditions between the 80% comfort acceptability limits. Cases 1 and 4 exhibit worse behaviour compared to the abovementioned strategies, with the classroom where cross-ventilation was applied requiring slightly less CDH than the classroom where single-sided ventilation was applied. Specifically, cross daytime ventilation requires 41.1 CDH; while, single-sided ventilation requires 42.9 CDH for thermal comfort conditions between the 80% acceptability limits.

Concerning the winter period, Case 4 shows significantly higher HDH compared to other cases, possibly due to the exposure of the classroom to the outdoor temperatures. As expected, the lowest HDH values are shown in Case 1 because it remained closed, thus minimising heat losses. Specifically, the HDH values are 63.5 and 20.8 for the Case 4 and Case 1 respectively for the 80% acceptability limits. It was observed that the less ventilation provided, the less heating degree-hours were required. Therefore, the HDH values for Case 2 and Case 3 are 24.9 and 28.4 respectively for the 80% acceptability limits,

Taking into account that the most usual strategy during the winter is Case 3, where windows are opened late in the morning when the temperature rises, while during summer the most usual strategy is Case 1, where single-sided ventilation is employed during the daytime, it can be derived that classrooms are more vulnerable during the summer period, which demonstrates higher degree hours values compare to the winter period. It should be noted that both periods under study represent the extreme case scenario periods in terms of outdoor conditions.

## 15.3. Results of dynamic simulation

The objective of this study is to investigate the effectiveness of different retrofitting measures and their impact on thermal comfort and energy performance of educational premises in current and future conditions of the climate, by employing a dynamic simulation software, in order to make buildings resilient under climate change. The objective is to find the optimum, sustainable solution to the problem with respect to the anthropogenic and natural environment. The **first phase** of analysis gave emphasis to the evaluation of natural ventilation as an effective cooling strategy through different window operation patterns using overheating criteria. The methodology to assess the impact of natural ventilation on the minimization of the overheating risk was described in **Chapter 11.4.4** and **Chapter 11.4.7**. The **second phase** of analysis includes passive optimization measures, i.e. those connected to the overall planning of a building's thermal envelope, those related to a building's operational phase, and those related to building geometry, i.e., solar shading control. In addition, heat recovery ventilation is also deemed effective for the provision of thermal comfort and indoor air quality in school buildings. The methodology to assess proposed adaptation measures was described in **Chapter 11.4.5** and **Chapter 11.4.7**. The **third phase** of analysis examines the energy performance of adaptation measures and their cost effectiveness based on the methodology described in **Chapter 11.4.6** and **Chapter 11.4.7.** The **fourth phase** of analysis identify the robustness of key input parameters of the cost effectiveness making a sensitivity analysis based on the methodology described in **Chapter 11.4.7**. The assessment of the resilience of school buildings provides valuable information in the effort to understand the necessity of producing measures of energy retrofitting, so as to contribute to policies and interventions that will lead to more energy-efficient, retrofitting solutions. Moreover, the study will inform all relevant social groups in detail about this issue and create conditions for energy education and environmental awareness for users of educational buildings and society in general. Finally, the design strategies used in this study may be applied to ensure a holistic design approach, one championing efficient, climate-responsive buildings as well as inform the preliminary design stage of other buildings in the future.

### *15.3.1. Assessment of proper operation of windows and overheating risk*

Simulation can predict the likelihood of overheating in typical classrooms of educational buildings. Table 15.4 presents the results of the three criteria in the middle class of the ground floor in different orientations for the current typical meteorological year, for 2050, and 2090 for the reference classroom while Table 15.5 shows the results of the proposed improvements using different operation of windows. Criterion 2 presents the weighted exceedance and criterion 3 shows the exceedance in hours.

#### *15.3.1.1. Typical Meteorological Year*

For the present TMY (Typical Meteorological Year) (Table 15.4), the base case of the south and north-oriented classroom, i.e. the classroom with the largest windows facing south and north respectively and the clerestories facing the opposite side, passed all the criteria (1-3). Specifically, the numbers of hours in the non-typical heating season when operative temperature exceeded *Tmax* is exactly 3% of the occupied time while indoor temperature never exceeded 4K compared to *Tmax*. However, east and west oriented classrooms failed to pass criterion 1 by 1%, while they passed criterion 2 and 3. South-oriented classrooms exhibit the lowest tendency for overheating due to lower solar gains because of existing overhangs.

The results show that providing night ventilation in any scenario has a positive contribution to the reduction of overheating risks. For the TMY, case 1, employing only the night ventilation strategy (Table 15.5a), has the most effective results in all orientations compared to the other cases. Specifically, night ventilation alone reduces the number of occupied hours when the operative temperature exceeds *Tmax* from 3% to 1% for the south-oriented classroom, from 3% to 2% for the north oriented classroom, and from 4% to 2% for the east and west-oriented classrooms meeting criterion 1 successfully. The strategy of night ventilation alone reduced the daily weighted exceedance value of criterion 2 by half, while, criterion 3 is also fulfilled.

It is worth noting that full day ventilation (case 4-Table 15.5d) produces the worst results compared to case 2 (Table 15.5b) and 3 (Table 15.5c) for all orientations. This is because indoor air temperatures follow the pattern of the external environment. Nevertheless, the risk of overheating during the full day (24-h) ventilation strategy is lower almost by half compared to the respective risk during daytime ventilation (reference scenario). Specifically, full-day ventilation (24h) reduces the number of occupied hours when the operative temperature exceeds *Tmax* from 3% to 2% for the south and north-oriented classroom, and from 4% to 2% for east and west-oriented classrooms. The daily weighted exceedance value of criterion 2, for the south-oriented classroom increased from 0.03 to 0.14, for the north-oriented classroom it reduced from 0.31 to 0.17 and for the west and east-oriented classrooms it reduced from 0.4 to 0.2. It thus, becomes clear that the full-day (24h) ventilation strategy results to improved indoor temperatures during the night compared to the daytime ventilation strategy.

Daytime ventilation only during recess time, in combination with night ventilation strategy (case 2), shows better performance than daytime ventilation until 12:50 in combination with night ventilation (case 3), because the internal environment is less influenced by external temperatures. Figure 15.3. shows the temperature patterns of internal operative temperature and external air temperature using different ventilation strategies in the typical meteorological year during August.

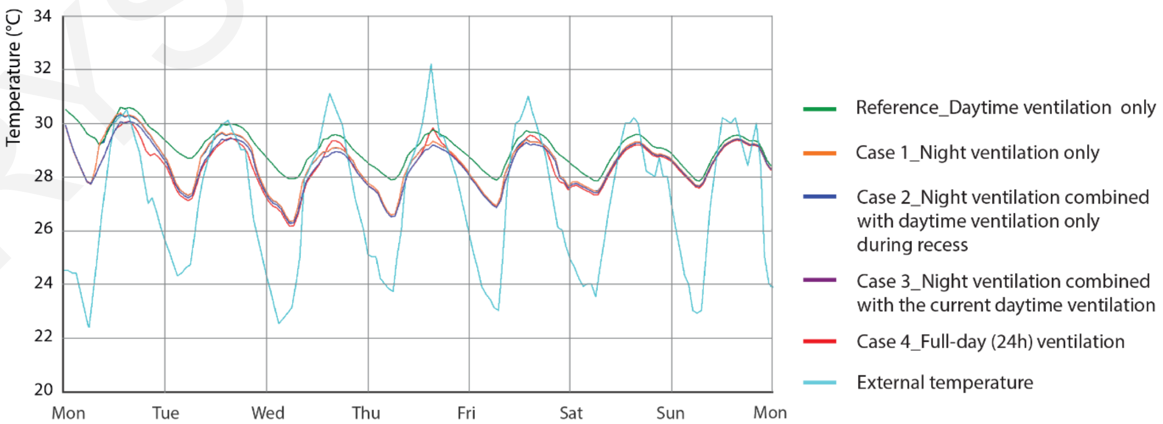



Figure 15.3. Indoor operative temperature and outdoor air temperature in August (16/8-22/8) for different ventilation strategies

*15.3.1.2. Future climatic conditions of 2050 and 2090*

Looking at the future climatic scenarios of 2050 and 2090, there is a clear tendency for severe overheating. Classrooms in all four orientations in the reference scenario failed all the criteria and were unable to cope with overheating predictions solely relying on the current passive cooling strategies (Table 15.4). In 2050, for the daytime ventilation strategy (reference scenario), more than half of the occupied period is predicted to suffer from overheating, while in 2090, more than 70% of the time. Moreover, a large number of hours exceed the limit of maximum absolute value of 4K which indicates that adaptive actions will be insufficient to restore personal comfort and that the vast majority of occupants will complain about excessive heat.

Although it was expected that the night ventilation strategy alone in 2050 (case 1- Table 15.5a) would be the most effective strategy for the reduction of overheating, it is worth noting that, the strategy that provides the lower numbers of overheating in all three criteria is the partial day and night ventilation (case 3- Table 15.5c). Daytime ventilation seems to be important in the future in removing the extensive heat produced in the indoor environment from internal sources and solar gains. The proposed improvement (case 3) can achieve a reduction of hours of the exceedance criterion by 28-35% in 2050s compared to the reference scenario. As also observed in TMY, in 2050, the south-oriented classroom shows the lowest overheating risk followed by the north-oriented classroom and then by the west and east-oriented classroom. The contribution of daytime ventilation is more prominent in 2090, where the full-day (24-h) ventilation strategy seems to be the most suitable for the reduction of occupied hours when the operative temperature exceeds Tmax (Table 15.5d) for the west and east-oriented classrooms. This is probably caused by the orientation of windows relevant to the prevailing winds (west) that allow heat losses from the classrooms. For south and north-oriented classrooms, daytime ventilation until noon, combined with night-ventilation, is the most suitable strategy. The proposed improvements can achieve a maximum reduction of hours of the exceedance criterion of 9-11% in 2090s. It is predicted that full-day (24h) ventilation will reduce the hours of exceedance from 68% to 62% in south-oriented classrooms, from 69% to 62% in north-oriented classrooms, from 74% to 66% in east-oriented classrooms and from 72% to 65% in west-oriented classrooms. Although night cooling has a positive impact on the reduction of the overheating risk in the future, it is still insufficient to create comfortable internal conditions and meet the criteria. Increased discomfort hours make the need for cooling predominant in order to achieve acceptable comfort conditions.

Table 15.4. TM52 criteria for the base case for different classroom orientations in line with climatic predictions

| **Day time ventilation only (Reference)** | | | | | | |
|---|---|---|---|---|---|---|
| | **TMY** | | **2050** | | **2090** | |
| **South** | | | | | | |
| **C1** | Pass | 3% | Fail | 53% | Fail | 68% |
| **C2** | Pass | 0.03 | Fail | 8.8 | Fail | 19.1 |
| **C3** | Pass | 0 | Fail | 42 | Fail | 192 |
| **North** | | | | | | |
| **C1** | Pass | 3% | Fail | 55% | Fail | 69% |
| **C2** | Pass | 0.31 | Fail | 9.4 | Fail | 19.9 |
| **C3** | Pass | 0 | Fail | 42 | Fail | 203 |
| **East** | | | | | | |
| **C1** | Fail | 4% | Fail | 64% | Fail | 74% |
| **C2** | Pass | 0.4 | Fail | 11.4 | Fail | 22.0 |
| **C3** | Pass | 0 | Fail | 51 | Fail | 244 |
| **West** | | | | | | |
| **C1** | Fail | 4% | Fail | 62% | Fail | 72% |
| **C2** | Pass | 0.4 | Fail | 13.0 | Fail | 23.9 |
| **C3** | Pass | 0 | Fail | 53 | Fail | 248 |

Table 15.5. TM52 criteria for different ventilation strategies (a) night ventilation alone, (b) daytime ventilation only during recess time and night cooling, (c) partial daytime ventilation and night ventilation, and (d) full-day ventilation), for different classroom orientations in line with climatic predictions. Optimum results in each climatic scenario are marked in bold.

| **A. Nighttime ventilation only (Case 1)** | | | | | | |
|---|---|---|---|---|---|---|
| | **TMY** | | **2050** | | **2090** | |
| **South** | | | | | | |
| **C1** | **Pass** | **1%** | Fail | 38% | Fail | 63% |
| **C2** | **Pass** | **0.01** | Pass | 5.5 | Fail | 15.5 |
| **C3** | **Pass** | **0** | Fail | 23 | Fail | 117 |
| **North** | | | | | | |
| **C1** | **Pass** | **2%** | Fail | 40% | Fail | 65% |
| **C2** | **Pass** | **0.13** | Pass | 5.9 | Fail | 16.0 |
| **C3** | **Pass** | **0** | Fail | 25 | Fail | 126 |
| **East** | | | | | | |
| **C1** | **Pass** | **2%** | Fail | 51% | Fail | 69% |
| **C2** | **Pass** | **0.2** | Fail | 8.0 | Fail | 18.6 |
| **C3** | **Pass** | **0** | Fail | 30 | Fail | 173 |
| **West** | | | | | | |
| **C1** | **Pass** | **2%** | Fail | 51% | Fail | 67% |
| **C2** | **Pass** | **0.2** | Fail | 8.9 | Fail | 19.8 |
| **C3** | **Pass** | **0** | Fail | 30 | Fail | 174 |

| **B. Daytime ventilation only during recess time and night cooling (Case 2)** | | | | | | |
|---|---|---|---|---|---|---|
| | **TMY** | | **2050** | | **2090** | |
| **South** | | | | | | |
| **C1** | Pass | 2% | Fail | 38% | Fail | 63% |

| | | | | | | |
|---|---|---|---|---|---|---|
| **C2** | Pass | 0.02 | Pass | 5.7 | Fail | 15.5 |
| **C3** | Pass | 0 | Fail | 25 | Fail | 120 |
| **North** | | | | | | |
| **C1** | Pass | 2% | Fail | 40% | Fail | 64% |
| **C2** | Pass | 0.15 | Pass | 6.0 | Fail | 16.1 |
| **C3** | Pass | 0 | Fail | 26 | Fail | 130 |
| **East** | | | | | | |
| **C1** | Pass | 2% | Fail | 50% | Fail | 68% |
| **C2** | Pass | 0.2 | Fail | 7.9 | Fail | 18.3 |
| **C3** | Pass | 0 | Fail | 32 | Fail | 173 |
| **West** | | | | | | |
| **C1** | Pass | 2% | Fail | 49% | Fail | 66% |
| **C2** | Pass | 0.2 | Fail | 8.8 | Fail | 19.6 |
| **C3** | Pass | 0 | Fail | 33 | Fail | 175 |

**C. Partial daytime ventilation and night ventilation (Case 3)**

| | **TMY** | | **2050** | | **2090** | |
|---|---|---|---|---|---|---|
| **South** | | | | | | |
| **C1** | Pass | 2% | **Fail** | **35%** | **Fail** | **62%** |
| **C2** | Pass | 0.02 | **Pass** | **5.6** | **Fail** | **14.9** |
| **C3** | Pass | 0 | **Fail** | **26** | **Fail** | **117** |
| **North** | | | | | | |
| **C1** | Pass | 2% | **Fail** | **37%** | **Fail** | **63%** |
| **C2** | Pass | 0.15 | **Pass** | **5.8** | **Fail** | **15.2** |
| **C3** | Pass | 0 | **Fail** | **28** | **Fail** | **123** |
| **East** | | | | | | |
| **C1** | Pass | 2% | **Fail** | **45%** | Fail | 69% |
| **C2** | Pass | 0.2 | **Fail** | **7.1** | Fail | 17.4 |
| **C3** | Pass | 0 | **Fail** | **31** | Fail | 152 |
| **West** | | | | | | |
| **C1** | Pass | 2% | **Fail** | **45%** | Fail | 66% |
| **C2** | Pass | 0.2 | **Fail** | **8.2** | Fail | 19.6 |
| **C3** | Pass | 0 | **Fail** | **34** | Fail | 175 |

**D. Full-day ventilation (Case 4)**

| | **TMY** | | **2050** | | **2090** | |
|---|---|---|---|---|---|---|
| **South** | | | | | | |
| **C1** | Pass | 2% | Fail | 36% | Fail | 62% |
| **C2** | Pass | 0.02 | Pass | 6.0 | Fail | 15.2 |
| **C3** | Pass | 0 | Fail | 29 | Fail | 126 |
| **North** | | | | | | |
| **C1** | Pass | 2% | Fail | 38% | Fail | 62% |
| **C2** | Pass | 0.17 | Fail | 6.3 | Fail | 15.6 |
| **C3** | Pass | 0 | Fail | 30 | Fail | 136 |
| **East** | | | | | | |
| **C1** | Pass | 2% | Fail | 46% | **Fail** | **66%** |
| **C2** | Pass | 0.2 | Fail | 7.4 | **Fail** | **16.9** |
| **C3** | Pass | 0 | Fail | 35 | **Fail** | **153** |
| **West** | | | | | | |
| **C1** | Pass | 2% | Fail | 45% | **Fail** | **65%** |
| **C2** | Pass | 0.2 | Fail | 8.4 | **Fail** | **18.5** |
| **C3** | Pass | 0 | Fail | 36 | **Fail** | **156** |

### *15.3.2. Assessment of adaptation measures in educational buildings with no provision of technical systems*

#### *15.3.2.1. Assessment of retrofitting scenarios during a typical meteorological year*

The results in degree hours and in terms of percentage reduction compared to the base case scenario for the TMY are summarized in Table 15.6. Each parameter was examined individually before examining the effect of selected combinations. A comparative examination of the results of the proposed improvements to the reference building, shows that the majority of measures achieve an increase in comfort hours, and the most effective of these include additional night ventilation; building fabric improvement with wall and roof insulation; external movable solar shading system and heat recovery ventilation system.

Focusing on the effect of the **insulation on the walls** (C1-C4), it becomes apparent that the inclusion of insulation consistently reduces heating degree hours (HDH) by 5-6.8% in the classroom on the first floor and the best option is the one with higher thickness. However, the situation is reversed for the summer season, as cooling degree hours (CDH) increase (12.6-15.2% depending on the thickness) due to lower heat losses from the wall surfaces.

The application of **roof insulation** (C5-C8) seems to be slightly more important in educational buildings as it significantly reduces the CDH by around 65-75% on the first floor depending on the thickness but is also beneficial for the winter period as it reduces HDH by 4.2-4.8%. The effect is reduced slightly on the ground floor.

The addition of **insulation on the ground floor** (C9-C11) reduces the HDH to a similar extent as the wall insulation, i.e., 15.1-17.6 and 4.9-5.7% reduction in the ground and first floor classrooms respectively; however, it increases the CDH as heat cannot be released in the ground and it is transferred to both the ground and first floor classrooms. Specifically, it increases the CDH by 13.7-16% on the first floor and 93.4-111.8% on the ground floor.

The **change of windows** (C12-C15) has a negative effect on the HDH as the g-value of the glass is reduced, which in turn reduces solar gains during the occupied hours and increases the heating demand. However, it has a positive impact on the CDH of the order of 2.8-6.9%. Therefore, it can be concluded that windows do not contribute significantly in the energy balance of educational buildings during the TMY.

Many studies highlight that **natural ventilation** is an important cooling strategy, not only for the Mediterranean region, but also for other climates. This study shows that cross ventilation during daytime (C16) can reduce CDH by about 10%. Night ventilation can enhance the conditions of the indoor environment during the next day and this study reveals that night ventilation alone can reduce CDH by about 46% (C18) and, when it is combined with cross ventilation during daytime (C17), it can reach 62% reduction of CDH in the first floor.

Concerning **solar shading control**, the study examined a variety of strategies that may stop overheating in the summer and thus contribute to the reduction energy demands. Considering that heating demands are higher than cooling demands, the external movable shading seems to be the most effective strategy for shading / heat gains control in the buildings under study. Movable shading (C21) can reduce the CDH considerably, by about 30.2% on the first floor and 62.6% on the ground floor classroom, without significantly affecting the HDH, as during winter periods windows are kept uncovered to exploit solar gains. On the other hand, fixed shading systems may regulate the indoor conditions during the summer, but may cause problems in winter.

Finally, **MVHR** (C22) can reduce total degree hours by only 8.6%. The low percentage is attributed to the poor insulation and airtightness of the building.

Although some individual passive strategies reduce heating and cooling degree hours significantly (as shown in Table 15.6), combined strategies may prove to be more effective solutions. First of all, it is worth mentioning that with only roof insulation and night ventilation (C27), CDH are eliminated by 96.8% and therefore no additional measure is required. This strategy reduces the total degree hours by 6.9%. However, when additional insulation is added on the walls in scenario C27 i.e., C28, then the building envelope performance improves with lower heat losses, and total degree hours reduced by 16.4% on the first-floor classroom compared to the reference building. Taking into consideration the mildest approach in terms of a complete thermal envelope refurbishment (C23) alone, the total degree hours reduce by 20.2% in the first-floor class i.e., 19.3% reduction of HDH and 53.2% reduction of CDH, while on the ground floor they reduce by 23.2%, i.e., 23.5% reduction of HDH and 15.1% increase of CDH. The high insulation levels on the ground floor have a negative effect during the summer period. Higher insulation on the roof and walls (C26) can reduce the total degree hours by 25.6% on the first-floor class and by 26.8% on the ground floor and more specifically, C26 can reduce the HDH by 24.4% and 27% and the CHD by 66.2% and 9.2% for the first and ground floor respectively. The significant variation of the cooling performance between ground and first floor is attributed to the floor insulation that affects the cooling performance in an adverse manner (C23-C26). In addition, it is interesting to note that on the ground floor classroom, the higher the insulation of the thermal envelope, the better the cooling performance (C23-C26). Moreover, in the individual scenarios, windows do not play an important role in the energy balance of the building. The addition of cross ventilation during daytime and nighttime in scenario C26, i.e., C30, decreases the CDH by another 33.3% compared to C26; and reduces total degree hours by 26.1% compared to the reference building. Adding a movable shading system to scenario C30, i.e., C31, does not really affect the total performance of the building, since applying roof insulation and factoring ventilation, almost zero cooling degree hours are achieved. Finally, as evident in C32 when adding heat recovery ventilation to C31, which combines all the passive strategies, it is found that this can significantly reduce the HDH by another 25.2%. Specifically, C32 reduced HDH by 49.6%, CDH by 100% and the total degree hours by 51%.

Considering the fact that educational buildings are not operational in the summer and that thermal requirements pertain primarily to heating, the thickness of the applied insulation plays an important role, as a greater thickness provides better comfort during the cold season. Additionally, the study shows that employing night ventilation eradicates the need for air conditioning during the day when students occupy the classroom.

Table 15.6. Predicted heating and cooling degree hours and percentage of their reduction using individual passive strategies and combinations thereof in south classrooms during hours of occupation (07:30-13:35) of the TMY using the 80% acceptability limit.

| TMY | | Occupied hours (07:30-13:35) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | First floor classroom | | | | | | Ground floor classroom | | | | | |
| | | Degree hours | | | Percentage of degree hours change (%) | | | Degree hours | | | Percentage of degree hours change (%) | | |
| | | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total |
| | REF. | 3187.6 | 90.7 | 3278.3 | - | - | - | 3487.1 | 30.8 | 3517.9 | - | - | - |
| Wall | C1 | 3013.5 | 102.1 | 3115.6 | -5.5 | 12.6 | -5.0 | 3305.3 | 34.9 | 3340.2 | -5.2 | 13.2 | -5.1 |
| | C2 | 2992.4 | 103.3 | 3095.6 | -6.1 | 13.9 | -5.6 | 3284.5 | 35.0 | 3319.6 | -5.8 | 13.7 | -5.6 |
| | C3 | 2984.3 | 103.8 | 3088.0 | -6.4 | 14.5 | -5.8 | 3276.1 | 35.1 | 3311.3 | -6.0 | 14.0 | -5.9 |
| | C4 | 2971.4 | 104.4 | 3075.8 | -6.8 | 15.2 | -6.2 | 3263.4 | 35.2 | 3298.6 | -6.4 | 14.2 | -6.2 |
| Roof | C5 | 3052.3 | 31.0 | 3083.4 | -4.2 | -65.8 | -5.9 | 3477.3 | 17.7 | 3495.0 | -0.3 | -42.7 | -0.7 |
| | C6 | 3099.5 | 25.4 | 3124.9 | -2.8 | -72.0 | -4.7 | 3530.9 | 16.4 | 3547.2 | 1.3 | -46.9 | 0.8 |
| | C7 | 3039.1 | 23.5 | 3062.5 | -4.7 | -74.1 | -6.6 | 3473.6 | 15.9 | 3489.5 | -0.4 | -48.5 | -0.8 |
| | C8 | 3035.7 | 22.4 | 3058.1 | -4.8 | -75.3 | -6.7 | 3472.5 | 15.6 | 3488.1 | -0.4 | -49.3 | -0.8 |
| Floor | C9 | 3032.1 | 103.1 | 3135.1 | -4.9 | 13.7 | -4.4 | 2959.9 | 59.6 | 3019.5 | -15.1 | 93.4 | -14.2 |
| | C10 | 3014.3 | 104.7 | 3119.0 | -5.4 | 15.4 | -4.9 | 2899.1 | 63.6 | 2962.7 | -16.9 | 106.3 | -15.8 |
| | C11 | 3007.1 | 105.2 | 3112.2 | -5.7 | 16.0 | -5.1 | 2874.8 | 65.3 | 2940.0 | -17.6 | 111.8 | -16.4 |
| Window | C12 | 3217.5 | 88.2 | 3305.7 | 0.9 | -2.8 | 0.8 | 3531.2 | 28.2 | 3559.4 | 1.3 | -8.6 | 1.2 |
| | C13 | 3203.9 | 90.2 | 3294.1 | 0.5 | -0.5 | 0.5 | 3537.9 | 27.0 | 3564.9 | 1.5 | -12.5 | 1.3 |
| | C14 | 3203.2 | 90.5 | 3293.7 | 0.5 | -0.2 | 0.5 | 3538.2 | 26.7 | 3564.9 | 1.5 | -13.2 | 1.3 |
| | C15 | 3300.9 | 84.4 | 3385.3 | 3.6 | -6.9 | 3.3 | 3656.4 | 22.4 | 3678.8 | 4.9 | -27.3 | 4.6 |
| Vent. | C16 | 3189.0 | 81.5 | 3270.5 | 0.0 | -10.1 | -0.2 | 3489.0 | 27.2 | 3516.1 | 0.1 | -11.7 | -0.1 |
| | C17 | 3190.5 | 34.5 | 3224.9 | 0.1 | -62.0 | -1.6 | 3502.4 | 9.8 | 3512.2 | 0.4 | -68.2 | -0.2 |
| | C18 | 3189.6 | 49.0 | 3238.6 | 0.1 | -45.9 | -1.2 | 3495.9 | 11.3 | 3507.2 | 0.3 | -63.4 | -0.3 |
| Shutter | C19 | 3224.3 | 90.5 | 3314.8 | 1.2 | -0.2 | 1.1 | 3529.9 | 30.7 | 3560.6 | 1.2 | -0.3 | 1.2 |
| | C20 | 3465.0 | 88.7 | 3553.7 | 8.7 | -2.1 | 8.4 | 3811.4 | 29.5 | 3840.9 | 9.3 | 4.3 | 9.2 |
| | C21 | 3196.1 | 63.3 | 3259.4 | 0.3 | -30.2 | -0.6 | 3532.5 | 11.5 | 3544.0 | 1.3 | -62.6 | 0.7 |
| MVHR | C22 | 2917.4 | 77.8 | 2995.3 | -8.5 | -14.2 | -8.6 | 2716.9 | 25.7 | 2742.7 | -7.4 | -16.5 | -7.5 |
| Combinations | C23 | 2573.0 | 42.5 | 2615.4 | -19.3 | -53.2 | -20.2 | 2667.1 | 35.5 | 2702.5 | -23.5 | 15.1 | -23.2 |
| | C24 | 2559.5 | 41.4 | 2600.8 | -19.7 | -54.4 | -20.7 | 2668.1 | 32.6 | 2700.7 | -23.5 | 5.8 | -23.2 |
| | C25 | 2477.8 | 33.4 | 2511.3 | -22.3 | -63.1 | -23.4 | 2605.0 | 29.3 | 2634.3 | -25.3 | -4.8 | -25.1 |
| | C26 | 2409.1 | 30.6 | 2439.7 | -24.4 | -66.2 | -25.6 | 2546.4 | 28.0 | 2574.3 | -27.0 | -9.2 | -26.8 |
| | C27 | 3049.8 | 2.9 | 3052.7 | -4.3 | -96.8 | -6.9 | 3495.2 | 4.4 | 3499.7 | 0.2 | -85.7 | -0.5 |
| | C28 | 2740.4 | 1.8 | 2742.1 | -14.0 | -98.1 | -16.4 | 3238.2 | 3.5 | 3241.8 | -7.1 | -88.5 | -7.9 |
| | C29 | 2488.6 | 0.8 | 2489.4 | -21.9 | -99.2 | -24.1 | 2623.9 | 1.6 | 2625.5 | -24.8 | -94.9 | -25.4 |
| | C30 | 2420.9 | 0.5 | 2421.4 | -24.1 | -99.5 | -26.1 | 2566.1 | 1.0 | 2567.2 | -26.4 | -96.7 | -27.0 |
| | C31 | 2411.0 | 0.0 | 2411.0 | -24.4 | -100.0 | -26.5 | 2560.2 | 0.0 | 2560.2 | -26.6 | -100.0 | -27.2 |
| | C32 | 1605.74 | 0.0 | 1605.74 | -49.6 | -100.0 | -51.0 | 1761.9 | 0 | 1761.9 | -49.5 | -100.0 | -49.9 |

*15.3.2.2. Assessment of retrofitting scenarios during future climatic conditions of 2050, 2090*

The results in degree hours compared to the base case scenario for the TMY, 2050s and 2090s respectively are summarized in Figure 15.4. The predicted heating and cooling degree hours and percentage of their reduction using individual passive strategies and combinations thereof in south classrooms during hours of occupation (07:30-13:35) in 2050 and 2090 using the 80% acceptability limit are summarized in Table 15.7 and Table 15.8. The results show that the efficiency of recommendations is differentiated in future conditions. The discussion below mainly involves the south classroom located on the first floor. The ground floor classroom exhibits similar patterns between ground and first floor in the future years of 2050 and 2090 as the TMY.

Specifically, in the south classroom located on the first floor, the contribution of insulation in the future is important as findings show that the percentage of reduction of degree hours increases as years progress. The application of wall insulation (C1-C4) in 2050 leads to a reduction of total degree hours in the range of 5.6%- 6.4% while in 2090 in the range of 5.4 to 6.7%. The application of roof insulation (C5-C8) seems to be of high importance even in the future, as the percentage reduction of total degree hours ranges between 8.2% to 9.7% in 2050 and between 12% to 14.2% in 2090. The application of floor insulation (C9-C11) is important for the heating period but it remains almost constant in terms of efficiency as the current climatic scenario. Particularly, in 2050 the reduction percentage of total degree hours ranges from 4.4% to 6.2% and in 2090 from 4.8% to 5.5%. Similarly, the application of floor insulation leads to the increase of cooling demand in both the ground and first floor classroom. However, the percentage of increase in the ground floor classroom becomes smaller compared to TMY. Particularly, in 2050 the percentage of increase of cooling degree hours ranges from 66.4 to 78.9% and in 2090 from 56.3 to 67.6%. The application of improved windows individually (C12-C15) is a measure that has no noticeable effect on the energy demands when considered individually. Although natural ventilation is an important strategy for the removal of heat gains, it becomes less efficient in the future due to higher minimum air temperatures in the summer (C16-18). Specifically, natural ventilation both during the day and night (C17) can reduce cooling degree hours by 56.3% in 2050s and by 52.9% in 2090 compared to the 62% reduction in TMY. Applying fixed solar shading systems (C19-C20) will have more adverse effect in future climatic scenarios than the current. In addition, the effect of movable shading (C21) is reduced in the future. Specifically, the cooling degree hours reduce by 22% in 2050 and by 19.5% in 2090 compared to the reduction of 30.2% during the TMY. Finally, the mechanical ventilation with heat recovery (MVHR) system (C22) is increasingly becoming more significant in the future for both thermal comfort and air quality. Particularly, in the non-insulated envelope of the reference building, total degree hours decrease by 11% and 12.1% for 2050 and 2090 respectively.

The importance of thermal insulation of the building envelope is also confirmed in scenario C26 which combines insulation on the walls, roofs, floors and incudes improved windows. Specifically, C26, in 2050 and 2090, reduces the total degree hours by 29.9% and 34.7% respectively. The effectiveness of combining natural ventilation and roof insulation (C27) is reduced in the future with percentages 91.4% and 84.9% for 2050 and 2090. The combination of all passive strategies (C31) under the future climatic scenarios shows a reduction of heating degree hours of 28.7% and the almost total elimination of the cooling degree hours with a percentage reduction of 99.9% in 2050 which in turn leads to a reduction of 32.1% of the total degree hours. However, in 2090, C31 reduces heating degree hours by 33.8% but cannot not avoid the need of active systems to maintain thermal comfort as it reduces cooling degree hours by 96.6%. The addition of heat recovery ventilation to the previous scenario C31 (i.e., C32) decreases heating and cooling degree hours by 58% and 99.8% respectively in 2050, with a total degree hours reduction of 60%. In 2090, it reduces the heating and cooling degree hours by 63.4% and 96.4% respectively and the total degree hours by 66.4%.

Table 15.7. Predicted heating and cooling degree hours and percentage of their reduction using individual passive strategies and combinations thereof in south classrooms during hours of occupation (07:30-13:35) in 2050 using the 80% acceptability limit.

| 2050 | | Occupied hours (07:30-13:35) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | First floor classroom | | | | | | Ground floor classroom | | | | | |
| | | Degree hours | | | Percentage of degree hours change (%) | | | Degree hours | | | Percentage of degree hours change (%) | | |
| | | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total |
| | Ref. | 2658.1 | 135.4 | 2793.5 | - | - | - | 2921.6 | 55.7 | 2977.3 | - | - | - |
| Wall | C1 | 2488.6 | 149.2 | 2637.8 | -6.4 | 10.2 | -5.6 | 2745.1 | 61.7 | 2806.7 | -6 | 10.6 | -5.7 |
| | C2 | 2483.4 | 150.6 | 2634 | -6.6 | 11.2 | -5.7 | 2736.4 | 62 | 2798.3 | -6.3 | 11.2 | -6 |
| | C3 | 2475.5 | 151.2 | 2626.7 | -6.9 | 11.6 | -6 | 2728.4 | 62.1 | 2790.4 | -6.6 | 11.3 | -6.3 |
| | C4 | 2463.6 | 152.1 | 2615.7 | -7.3 | 12.3 | -6.4 | 2716.2 | 62.2 | 2778.4 | -7 | 11.7 | -6.7 |
| Roof | C5 | 2506.3 | 57.1 | 2563.5 | -5.7 | -57.8 | -8.2 | 2911.5 | 34.7 | 2946.2 | -0.3 | -37.7 | -1 |
| | C6 | 2491.3 | 47.6 | 2538.9 | -6.3 | -64.8 | -9.1 | 2907.9 | 32.5 | 2940.4 | -0.5 | -41.6 | -1.2 |
| | C7 | 2484.7 | 44.2 | 2528.9 | -6.5 | -67.3 | -9.5 | 2906.3 | 31.7 | 2938 | -0.5 | -43.1 | -1.3 |
| | C8 | 2480.3 | 42.6 | 2522.8 | -6.7 | -68.6 | -9.7 | 2904.9 | 31.3 | 2936.2 | -0.6 | -43.8 | -1.4 |
| Floor | C9 | 2521.1 | 149.7 | 2670.8 | -5.2 | 10.5 | -4.4 | 2415.4 | 92.8 | 2508.2 | -17.3 | 66.4 | -15.8 |
| | C10 | 2504.3 | 151.5 | 2655.7 | -5.8 | 11.8 | -4.9 | 2356.5 | 97.7 | 2454.1 | -19.3 | 75.2 | -17.6 |
| | C11 | 2467.5 | 152.1 | 2619.6 | -7.2 | 12.3 | -6.2 | 2267.2 | 99.7 | 2366.9 | -22.4 | 78.9 | -20.5 |
| Window | C12 | 2660.7 | 132.4 | 2793.1 | 0.1 | -2.2 | 0 | 2974.8 | 52.5 | 3027.3 | 1.8 | -5.8 | 1.7 |
| | C13 | 2655.6 | 134.5 | 2790.1 | -0.1 | -0.7 | -0.1 | 2988.9 | 51.4 | 3040.3 | 2.3 | -7.7 | 2.1 |
| | C14 | 2656.1 | 134.8 | 2790.9 | -0.1 | -0.5 | -0.1 | 2990 | 51.3 | 3041.2 | 2.3 | -8 | 2.1 |
| | C15 | 2757.8 | 128.3 | 2886.1 | 3.7 | -5.2 | 3.3 | 3115.5 | 45.9 | 3161.3 | 6.6 | -17.7 | 6.2 |
| Vent. | C16 | 2659.1 | 123.9 | 2783 | 0 | -8.5 | -0.4 | 2922.5 | 50.4 | 2972.8 | 0 | -9.7 | -0.2 |
| | C17 | 2671.3 | 59.2 | 2730.5 | 0.5 | -56.3 | -2.3 | 2935.4 | 20.9 | 2956.2 | 0.5 | -62.6 | -0.7 |
| | C18 | 2671 | 78.7 | 2749.7 | 0.5 | -41.9 | -1.6 | 2932.7 | 23.6 | 2956.3 | 0.4 | -57.7 | 0.7 |
| Shutter | C19 | 2743.3 | 135 | 2878.3 | 3.2 | -0.3 | 3 | 3105.6 | 55.4 | 3161 | 6.3 | -0.7 | 6.2 |
| | C20 | 2928 | 133.9 | 3061.9 | 10.2 | -1.1 | 9.6 | 3290.4 | 54.5 | 3344.9 | 12.6 | -2.3 | 12.3 |
| | C21 | 2684.5 | 105.7 | 2790.2 | 1 | -22 | -0.1 | 2982.1 | 29.2 | 3011.3 | 12.2 | -78.4 | 7.8 |
| MVHR | C22 | 2359.8 | 127.2 | 2487 | -11.2 | -6.1 | -11 | 2235.3 | 51.8 | 2287.1 | -15.9 | -61.7 | -18.1 |
| Combinations | C23 | 2071 | 70.5 | 2141.5 | -22.1 | -47.9 | -23.3 | 1909.3 | 59.5 | 1968.8 | -28.2 | -56.1 | -29.5 |
| | C24 | 2051.7 | 68.5 | 2120.2 | -22.8 | -49.4 | -24.1 | 1907.5 | 55.7 | 1963.2 | -28.2 | -58.9 | -29.7 |
| | C25 | 1970.6 | 56 | 2026.6 | -25.9 | -58.7 | -27.5 | 1871.1 | 50 | 1921.1 | -29.6 | -63.1 | -31.2 |
| | C26 | 1907.3 | 51.8 | 1959.1 | -28.2 | -61.8 | -29.9 | 1835.6 | 47.5 | 1883 | -30.9 | -65 | -32.6 |
| | C27 | 2488.3 | 11.6 | 2499.9 | -6.4 | -91.4 | -10.5 | 2511.9 | 11.4 | 2523.3 | -5.5 | -91.6 | -9.7 |
| | C28 | 2190.7 | 10.1 | 2200.8 | -17.6 | -92.5 | -21.2 | 2329.2 | 10.9 | 2340.1 | -12.4 | -91.9 | -16.2 |
| | C29 | 1974.1 | 7.1 | 1981.2 | -25.7 | -94.7 | -29.1 | 1879 | 8 | 1886.9 | -29.3 | -94.1 | -32.5 |
| | C30 | 1911.2 | 5.6 | 1916.8 | -28.1 | -95.9 | -31.4 | 1843.7 | 7 | 1850.7 | -30.6 | -94.8 | -33.7 |
| | C31 | 1896 | 0.2 | 1896.2 | -28.7 | -99.9 | -32.1 | 1837.5 | 0.5 | 1838.1 | -37.1 | -99.0 | -38.3 |
| | C32 | 1115.8 | 0.2 | 1116.1 | -58 | -99.8 | -60 | 1186 | 0.3 | 1186.3 | -59.4 | -99.5 | -60.2 |

Table 15.8. Predicted heating and cooling degree hours and percentage of their reduction using individual passive strategies and combinations thereof of south classrooms during hours of occupation (07:30-13:35) in 2090 using the 80% acceptability limit.

| 2090 | | Occupied hours (07:30-13:35) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | First floor classroom | | | | | | Ground floor classroom | | | | | |
| | | Degree hours | | | Percentage of degree hours change (%) | | | Degree hours | | | Percentage of degree hours change (%) | | |
| | | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total |
| | REF. | 2187.5 | 213.4 | 2400.9 | | | | 2388.6 | 96.5 | 2485.2 | | | |
| Wall | C1 | 2037.2 | 233.4 | 2270.6 | -6.9 | 9.4 | -5.4 | 2246.1 | 104.9 | 2351.0 | -6.0 | 8.7 | -5.4 |
| | C2 | 2019.2 | 235.7 | 2254.9 | -7.7 | 10.5 | -6.1 | 2227.0 | 105.3 | 2332.3 | -6.8 | 9.1 | -6.1 |
| | C3 | 2012.1 | 236.5 | 2248.6 | -8.0 | 10.9 | -6.3 | 2219.6 | 105.5 | 2325.1 | -7.1 | 9.3 | -6.4 |
| | C4 | 2001.2 | 237.9 | 2239.1 | -8.5 | 11.5 | -6.7 | 2207.9 | 105.8 | 2313.7 | -7.6 | 9.6 | -6.9 |
| Roof | C5 | 2004.1 | 109.3 | 2113.4 | -8.4 | -48.8 | -12.0 | 2380.4 | 69.7 | 2450.1 | -0.3 | -27.8 | -1.4 |
| | C6 | 1985.8 | 95.8 | 2081.7 | -9.2 | -55.1 | -13.3 | 2376.1 | 66.5 | 2442.6 | -0.5 | -31.1 | -1.7 |
| | C7 | 1977.8 | 90.8 | 2068.6 | -9.6 | -57.4 | -13.8 | 2373.8 | 65.3 | 2439.1 | -0.6 | -32.4 | -1.9 |
| | C8 | 1972.8 | 88.3 | 2061.0 | -9.8 | -58.6 | -14.2 | 2372.8 | 64.7 | 2437.5 | -0.7 | -33.0 | -1.9 |
| Floor | C9 | 2051.7 | 234.8 | 2286.4 | -6.2 | 10.0 | -4.8 | 1932.5 | 150.9 | 2083.4 | -19.1 | 56.3 | -16.2 |
| | C10 | 2036.5 | 237.4 | 2273.9 | -6.9 | 11.3 | -5.3 | 1878.4 | 158.7 | 2037.1 | -21.4 | 64.4 | -18.0 |
| | C11 | 2030.4 | 238.6 | 2268.9 | -7.2 | 11.8 | -5.5 | 1857.2 | 161.8 | 2019.0 | -22.2 | 67.6 | -18.8 |
| Window | C12 | 2215.4 | 209.1 | 2424.5 | 1.3 | -2.0 | 1.0 | 2451.9 | 92.4 | 2544.3 | 2.6 | -4.3 | 2.4 |
| | C13 | 2210.9 | 211.8 | 2422.7 | 1.1 | -0.7 | 0.9 | 2465.0 | 91.6 | 2556.6 | 3.2 | -5.1 | 2.9 |
| | C14 | 2211.0 | 212.1 | 2423.1 | 1.1 | -0.6 | 0.9 | 2466.2 | 91.5 | 2557.6 | 3.2 | -5.2 | 2.9 |
| | C15 | 2307.0 | 202.8 | 2509.9 | 5.5 | -4.9 | 4.5 | 2584.2 | 84.6 | 2668.8 | 8.2 | -12.3 | 7.4 |
| Vent. | C16 | 2188.8 | 197.1 | 2385.9 | 0.1 | -7.6 | -0.6 | 2411.4 | 89.0 | 2500.4 | 1.0 | -7.8 | 0.6 |
| | C17 | 2189.1 | 100.5 | 2289.5 | 0.1 | -52.9 | -4.6 | 2416.2 | 42.0 | 2458.2 | 1.2 | -56.5 | -1.1 |
| | C18 | 2188.8 | 135.7 | 2324.5 | 0.1 | -36.4 | -3.2 | 2411.7 | 49.1 | 2460.8 | 1.0 | -49.2 | -1.0 |
| Shutter | C19 | 2301.4 | 212.6 | 2514.0 | 5.2 | -0.4 | 4.7 | 2579.5 | 96.0 | 2675.5 | 8.0 | -0.5 | 7.7 |
| | C20 | 2483.3 | 210.9 | 2694.2 | 13.5 | -1.2 | 12.2 | 2758.3 | 94.9 | 2853.2 | 15.5 | -1.6 | 14.8 |
| | C21 | 2203.0 | 171.8 | 2374.8 | 0.7 | -19.5 | -1.1 | 2457.8 | 62.0 | 2519.8 | 2.9 | -35.8 | 1.4 |
| MVHR | C22 | 1908.4 | 201.2 | 2109.6 | -12.8 | -5.7 | -12.1 | 1841.5 | 89.9 | 1931.3 | -15.8 | -57.9 | -19.6 |
| Combinations | C23 | 1609.2 | 133.1 | 1742.3 | -26.4 | -37.6 | -27.4 | 1533 | 111.4 | 1644.4 | -29.9 | -47.8 | -31.5 |
| | C24 | 1595 | 130.9 | 1725.8 | -27.1 | -38.7 | -28.1 | 1531.1 | 106.7 | 1637.8 | -30.0 | -50.0 | -31.8 |
| | C25 | 1518.5 | 113.2 | 1631.7 | -30.6 | -46.9 | -32.0 | 1495.9 | 99.2 | 1595.1 | -31.6 | -53.5 | -33.6 |
| | C26 | 1461 | 106.7 | 1567.7 | -33.2 | -50.0 | -34.7 | 1462.3 | 96 | 1558.3 | -33.2 | -55.0 | -35.1 |
| | C27 | 1982.7 | 32.2 | 2014.9 | -9.4 | -84.9 | -16.1 | 2078.5 | 28.8 | 2107.3 | -5.0 | -86.5 | -12.2 |
| | C28 | 1706.5 | 30.1 | 1736.5 | -22.0 | -85.9 | -27.7 | 1906.8 | 28.4 | 1935.2 | -12.8 | -86.7 | -19.4 |
| | C29 | 1522.4 | 25.3 | 1547.7 | 030.4 | -88.1 | -35.5 | 1503.4 | 23.6 | 1527 | -31.3 | -88.9 | -36.4 |
| | C30 | 1465 | 22.3 | 1487.3 | -3.03 | -89.5 | -38.1 | 1470.4 | 22.2 | 1492.6 | -32.8 | -89.6 | -37.8 |
| | C31 | 1449.2 | 7.3 | 1456.5 | -33.8 | -96.6 | -39.3 | 1461.1 | 7.1 | 1468.2 | -38.8 | -92.6 | -40.9 |
| | C32 | 799.8 | 7.6 | 807.4 | -63.4 | -96.4 | -66.4 | 872 | 8.3 | 880.3 | -60.1 | -96.1 | -63.3 |

### *15.3.3. Energy ranking and cost effectiveness of adaptation measures*

#### *15.3.3.1. Energy demand and retrofit ranking*

The results of predicting primary energy consumption for the south-oriented classroom of the first and ground floor in kWh/m$^2$/yr and in terms of percentage change compared to the base case scenario for the TMY are summarized in Table 15.9. The analysis was made for the academic year. Each parameter was examined individually before examining the effect of the selected combinations. A comparative examination of the results of the retrofitting scenarios to the reference building, shows that the majority of measures achieve an increase in comfort hours and reduction of energy use, and the most effective of these include heat recovery ventilation system, building fabric improvement with wall and roof insulation, and additional night ventilation through an extractor fan.

Table 15.9. Predicted heating and cooling primary energy consumption and percentage of change compared to reference building using individual passive strategies and combinations thereof of south facing classrooms during hours of occupation (07:30-13:35) of the TMY.

**Occupied hours (07:30-13:35)**

| TMY | First floor classroom | | | | | | Ground floor classroom | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Primary Energy Consumption (kWh/m²/year) | | | Percentage change of primary energy (%) | | | Primary Energy Consumption (kWh/m²/year) | | | Percentage change of primary energy (%) | | |
| | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total |
| **Reference** | 67.9 | 9.4 | 77.2 | - | - | - | 68.2 | 6.9 | 75.1 | - | - | - |
| **C1** | 64.1 | 6.7 | 70.8 | -5.5 | -28.3 | -8.3 | 64.3 | 4.3 | 68.6 | -5.7 | -38.0 | -8.7 |
| **C2** | 63.7 | 6.7 | 70.4 | -6.2 | -28.0 | -8.8 | 63.9 | 4.3 | 68.1 | -6.4 | -37.9 | -9.3 |
| **C3** | 63.5 | 6.8 | 70.2 | -6.5 | -27.9 | -9.1 | 63.7 | 4.3 | 68.0 | -6.7 | -37.9 | -9.5 |
| **C4** | 63.2 | 6.8 | 70.0 | -6.9 | -27.7 | -9.4 | 63.4 | 4.3 | 67.7 | -7.1 | -37.8 | -9.9 |
| **C5** | 59.7 | 4.6 | 64.3 | -12.0 | -51.2 | -16.7 | 66.6 | 3.7 | 70.3 | -2.4 | -46.5 | -6.4 |
| **C6** | 58.8 | 4.3 | 63.1 | -13.4 | -53.9 | -18.3 | 66.4 | 3.6 | 70.0 | -2.7 | -47.3 | -6.8 |
| **C7** | 58.4 | 4.2 | 62.6 | -14.0 | -54.9 | -19.0 | 66.3 | 3.6 | 69.9 | -2.9 | -47.6 | -7.0 |
| **C8** | 58.1 | 4.2 | 62.3 | -14.4 | -55.4 | -19.3 | 66.2 | 3.6 | 69.8 | -3.0 | -47.8 | -7.1 |
| **C9** | 65.2 | 6.7 | 71.9 | -4.0 | -28.3 | -6.9 | 57.8 | 4.9 | 62.8 | -15.2 | -28.3 | -16.4 |
| **C10** | 64.9 | 6.7 | 71.6 | -4.4 | -28.0 | -7.2 | 56.7 | 5.0 | 61.7 | -16.9 | -26.9 | -17.8 |
| **C11** | 64.8 | 6.8 | 71.5 | -4.5 | -27.8 | -7.4 | 56.2 | 5.1 | 61.3 | -17.6 | -26.3 | -18.4 |
| **C12** | 68.2 | 6.3 | 74.5 | 0.5 | -33.0 | -3.5 | 68.8 | 4.0 | 72.8 | 0.8 | -42.4 | -3.1 |
| **C13** | 68.0 | 6.2 | 74.2 | 0.3 | -33.8 | -3.9 | 68.8 | 3.9 | 72.7 | 0.9 | -44.0 | -3.2 |
| **C14** | 67.8 | 6.2 | 74.0 | -0.1 | -33.8 | -4.2 | 68.6 | 3.8 | 72.4 | 0.5 | -44.3 | -3.6 |
| **C15** | 68.0 | 6.1 | 74.1 | 0.2 | -34.6 | -4.0 | 68.9 | 3.8 | 72.6 | 1.0 | -45.4 | -3.3 |
| **C16** | 67.9 | 6.6 | 74.4 | 0.0 | -30.0 | -3.6 | 68.2 | 4.4 | 72.6 | 0.0 | -36.7 | -3.4 |
| **C17** | 67.9 | 5.4 | 73.3 | 0.0 | -42.5 | -5.1 | 68.2 | 3.6 | 71.9 | 0.0 | -47.0 | -4.3 |
| **C18** | 67.9 | 5.2 | 73.0 | 0.0 | -44.8 | -5.4 | 68.2 | 3.4 | 71.6 | 0.0 | -51.2 | -4.7 |
| **C19** | 67.2 | 6.1 | 73.3 | -1.0 | -34.7 | -5.1 | 68.0 | 4.0 | 72.0 | -0.3 | -42.0 | -4.2 |
| **C20** | 72.1 | 6.6 | 78.7 | 6.2 | -29.4 | 1.9 | 72.8 | 4.2 | 77.1 | 6.7 | -38.2 | 2.6 |
| **C21** | 67.9 | 6.1 | 74.0 | 0.1 | -35.0 | -4.2 | 68.3 | 3.8 | 72.1 | 0.1 | -44.5 | -4.0 |
| **C22** | 33.5 | 6.2 | 39.7 | -50.6 | -34.3 | -48.7 | 33.9 | 4.0 | 37.9 | -50.3 | -42.0 | -49.5 |
| **C23** | 25.3 | 4.1 | 29.4 | -62.8 | -56.0 | -62.0 | 32.2 | 3.5 | 35.7 | -52.8 | -48.8 | -52.4 |
| **C24** | 24.9 | 4.0 | 28.9 | -63.3 | -56.9 | -62.5 | 32.1 | 3.5 | 35.6 | -52.9 | -49.1 | -52.6 |
| **C25** | 25.0 | 3.6 | 28.6 | -63.2 | -61.6 | -63.0 | 31.9 | 3.2 | 35.2 | -53.2 | -52.7 | -53.2 |
| **C26** | 24.6 | 3.5 | 28.2 | -63.7 | -62.4 | -63.5 | 31.8 | 3.2 | 35.1 | -53.3 | -52.9 | -53.3 |
| **C27** | 19.7 | 4.1 | 23.9 | -70.9 | -55.9 | -69.1 | 27.5 | 3.5 | 31.1 | -59.6 | -48.4 | -58.6 |
| **C28** | 19.3 | 4.0 | 23.3 | -71.6 | -56.9 | -69.8 | 27.4 | 3.5 | 30.9 | -59.8 | -48.8 | -58.8 |
| **C29** | 19.5 | 4.1 | 23.6 | -71.3 | -55.9 | -69.4 | 27.3 | 3.5 | 30.9 | -59.9 | -48.5 | -58.9 |
| **C30** | 19.0 | 4.0 | 23.0 | -72.0 | -57.0 | -70.2 | 27.2 | 3.5 | 30.7 | -60.1 | -48.8 | -59.1 |
| **C31** | 19.2 | 3.6 | 22.8 | -71.7 | -61.7 | -70.5 | 27.1 | 3.3 | 30.3 | -60.3 | -52.6 | -59.6 |
| **C32** | 18.8 | 3.5 | 22.3 | -72.4 | -62.6 | -71.2 | 26.9 | 3.2 | 30.2 | -60.5 | -52.9 | -59.8 |
| **C33** | 19.9 | 3.6 | 23.5 | -70.7 | -61.1 | -69.6 | 27.9 | 3.2 | 31.1 | -59.1 | -54.1 | -58.6 |
| **C34** | 19.4 | 3.5 | 23.0 | -71.4 | -62.3 | -70.3 | 27.8 | 3.1 | 30.9 | -59.3 | -54.5 | -58.8 |
| **C35** | 19.9 | 3.2 | 23.1 | -70.7 | -66.3 | -70.2 | 27.9 | 2.9 | 30.8 | -59.2 | -57.7 | -59.0 |
| **C36** | 19.6 | 3.1 | 22.8 | -71.1 | -66.4 | -70.5 | 27.7 | 2.9 | 30.6 | -59.5 | -57.8 | -59.3 |
| **C37** | 19.5 | 3.1 | 22.5 | -71.3 | -67.2 | -70.8 | 27.7 | 2.9 | 30.6 | -59.3 | -58.0 | -59.2 |
| **C38** | 19.2 | 3.1 | 22.2 | -71.7 | -67.3 | -71.2 | 27.5 | 2.9 | 30.4 | -59.6 | -58.1 | -59.5 |
| **C39** | 15.4 | 3.5 | 18.9 | -77.3 | -62.8 | -75.6 | 16.2 | 3.2 | 19.4 | -76.2 | -53.5 | -74.1 |
| **C40** | 15.4 | 3.9 | 19.2 | -77.4 | -58.8 | -75.1 | 16.2 | 3.5 | 19.7 | -76.3 | -48.5 | -73.7 |
| **C41** | 15.2 | 3.0 | 18.2 | -77.7 | -67.7 | -76.5 | 16.0 | 2.8 | 18.8 | -76.6 | -58.5 | -74.9 |
| **C42** | 14.6 | 2.9 | 17.6 | -78.5 | -68.7 | -77.3 | 15.8 | 2.8 | 18.6 | -76.8 | -58.9 | -75.2 |

Figure 15.4 shows the ranking of retrofitting scenarios individually based on the mean reduction of total primary energy consumption for the classrooms on the first and ground floor while Figure 15.5 shows the contribution of retrofitting scenarios for the reduction of heating and cooling primary energy consumption separately. The higher the energy reduction of primary energy, the higher ranking the retrofitting scenario has.

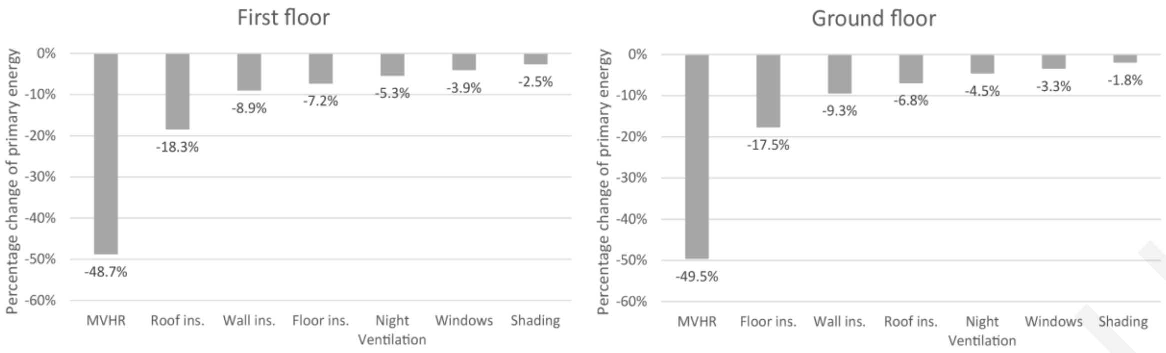



Figure 15.4. The ranking of retrofit options according to the total primary energy saving in the south-oriented classrooms of the first and ground floor.

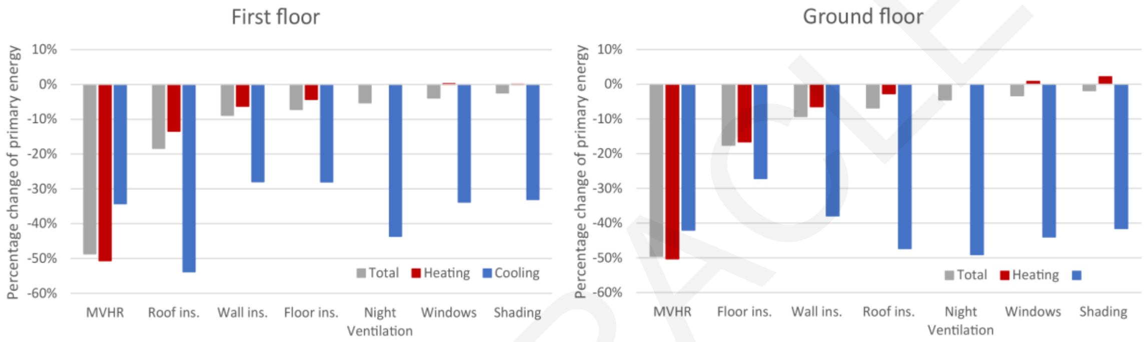



Figure 15.5. The percentage change of total primary, heating and cooling energy consumption in the south-oriented classrooms of the first and ground floor.

It is found that, providing a heat recovery ventilation unit has the highest energy-saving ranking at about 49% both on the first and ground floor classrooms. In a classroom that has its roof exposed to the external environment, the roof insulation is the second most important retrofitting option while in a classroom that it is located on the ground floor, floor insulation is the second important retrofitting option with a reduction of 18%. Adding insulation on the wall also has high ranking, by minimizing the total primary energy by about 9%, while night ventilation lowers the total primary energy consumption by about 5%. Windows provide a reduction of primary energy by about 3-4%. Shading devices have a small effect on the total energy saving measured at 2%, as classrooms are located south and the overhang created by the external corridor is considered adequate.

Focusing on the effects of the insulation on the **walls** (C1-C4), it becomes apparent that the inclusion of insulation consistently reduces heating primary energy consumption by 6-7% in the classroom on the first floor and the best option is the one with the higher thickness. During the summer season, cooling primary energy consumption decreases by 27-28% depending on the thickness. The higher the thickness, the lower the decrease of the cooling demand due to the isolation of heat gains inside the building envelope.

The application of **roof** insulation (C5-C8) seems to be the most important in educational buildings as it significantly reduces the cooling primary energy consumption by around 52-55% on the first floor depending on the thickness, while it is also beneficial for the winter period as it reduces heating primary energy consumption by about 12-14%. The effect of cooling saving is reduced slightly on the ground floor with a percentage of about 47-48% while the reduction of heating primary energy consumption ranges from about 2% to 3%.

The addition of insulation on the **ground floor** (C9-C11) reduces the heating primary energy consumption by about 4-5% and 15-17% reduction on the ground and first floor classrooms respectively, and the cooling primary energy consumption by about 28%. Again, the thicker the insulation of the ground floor is, the lower the reduction of cooling demands.

The replacement of **windows** (C12-C15) has a negative effect on the heating primary energy consumption by about 1%, as the g-value of the glass is reduced, which in turn reduces solar gains during the occupied hours and increases the heating demand. However, it has a positive impact on the reduction of cooling demands by 33-35% on the first floor and 42-45% on the ground floor. The overall contribution of windows to the energy saving of educational buildings during the TMY is not significant; however, they may have more impact in the future when temperatures will rise.

This study shows that cross **ventilation** during daytime (C16) can reduce cooling demand by about 30%. Night ventilation can enhance the conditions of the indoor environment during the next day and this study reveals that night ventilation alone can reduce cooling energy demand by about 43% (C17) and, when it is combined with cross ventilation during daytime (C18), it can reach a 45% reduction of cooling primary energy consumption on the first floor.

Concerning **solar shading control**, the study examines a variety of strategies that may stop overheating in the summer and thus contribute to the reduction of energy demands. Considering that heating demands are higher than cooling demands, external movable shading seems to be the most effective strategy for shading / heat gains control in the buildings under study. Movable shading (C21) can reduce the cooling primary energy consumption by about 35% on the first floor and by 45% on the ground floor classroom, without significantly affecting the heating demand, as during winter periods windows are kept uncovered to exploit solar gains. On the other hand, fixed shading systems may regulate the indoor conditions during the summer, but may cause problems in winter.

Finally, **MVHR** (C22) can reduce total primary energy consumption considerably by 49%. Heat recovery ventilation helps both heating and cooling savings as well as air quality of the classrooms.

Figure 15.6 shows the primary energy consumption of heating and cooling of individual retrofitting scenarios during the academic period in the south oriented classroom of the first and ground floor.

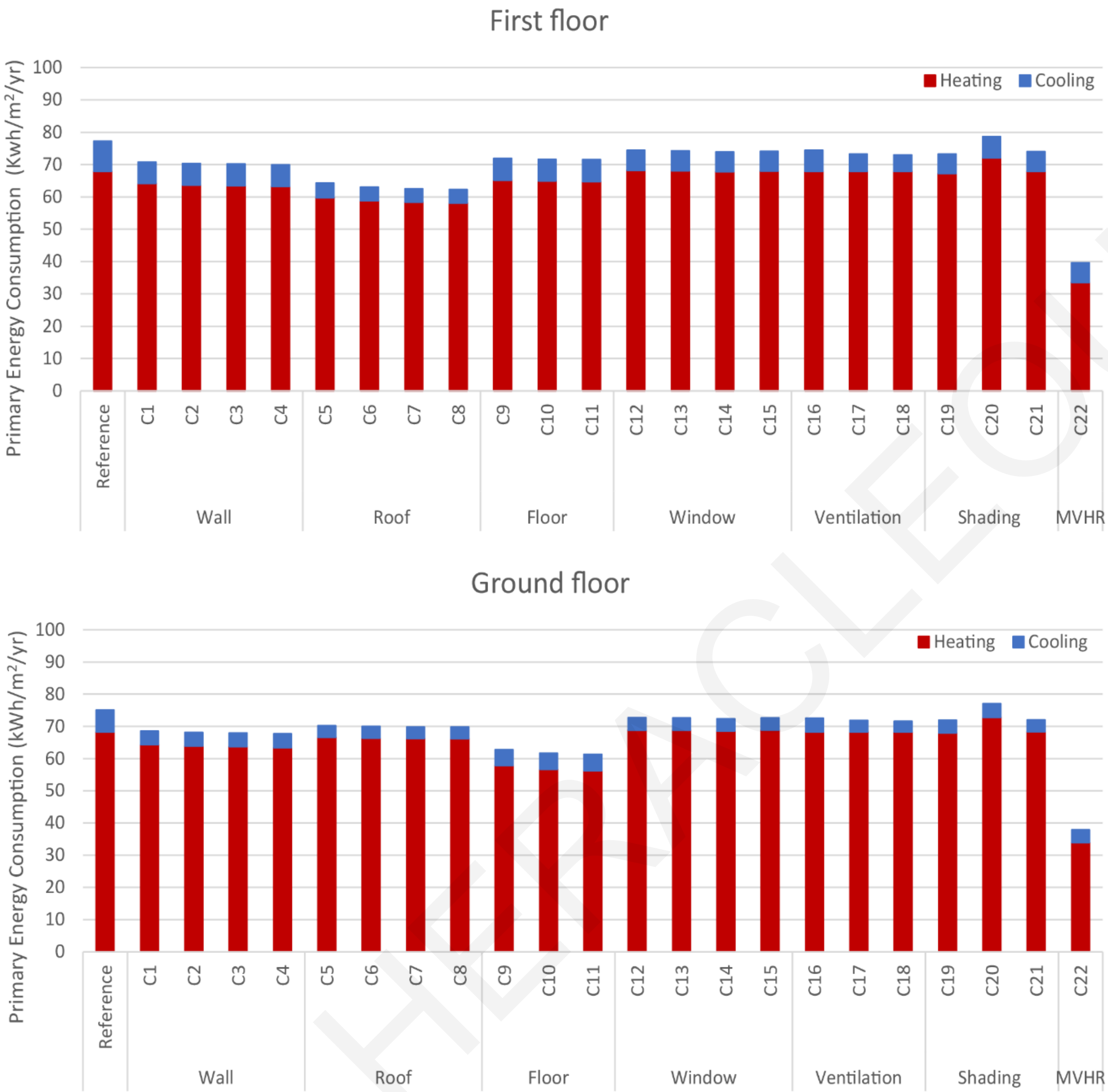



Figure 15.6. Primary energy consumption of the individual retrofitting scenarios during the academic period in the south oriented classroom of the first and ground floor.

The combinations of retrofit scenarios are performed while taking into account that adaptation measures should satisfy the provision of the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020 onwards, as well as the installation difficulties involved in each case. The combinations are categorized into light, medium and advanced retrofitting. Below the results of the south-oriented classroom on the first floor are summarized.

Taking into account that MVHR and roof insulation is the most effective solutions for the reduction of primary energy consumption, cases C23 and C24 examine those retrofitting scenarios with 10cm and 15cm thicknesses of insulation at ,achieving a total reduction of 62% and 62.5% respectively.

Cases C25 and C26 in comparison to previous scenarios C23 and C24 include additional ventilation during the day and night through an extractor fan and achieve a total reduction of primary energy consumption by 63% and 63.5% respectively. As it is evident, when the building is supported by a technical system, night ventilation is not as sufficient as when the building is free running, as it cannot lower indoor air temperatures below 26 °C. When the building is free running, the adaptive comfort standard allows for higher temperatures in the building and therefore the contribution of natural ventilation is higher in lowering degree hours. In addition, by achieving a heat recovery ventilation of 200 l/s, night ventilation through heat recovery is adequate to reduce indoor temperature at a great extent and the provision of additional ventilation fan that reaches 1000 l/s does not seem necessary.

Cases C27-C30 examine different thicknesses of insulation added to the wall in the aforementioned scenarios C23 and C24. Specifically, 8cm and 10cm of rockwool insulation were selected for analysis. C27 and C28 include an added 8cm of insulation to the ones in scenarios C23 and C24, while C29 and C30 include an added 10cm of insulation to the ones in scenarios C23 and C24 respectively. The results show that an overall reduction of the total primary energy consumption of 69.1-70.2% was achieved, depending on the insulation thickness. The higher the insulation, the lower the total primary energy consumption.

Cases C31 and C32 examine added ventilation to the aforementioned scenarios C29 and C30 in order to examine if an increased ventilation rate is more effective in a more insulated building envelope. As observed, the difference between C29/C30 and C31/C32 is small reaching a reduction of 70.5% and 71.2% for C31 and C32 respectively.

Cases C33 and C34 include added, improved windows to the aforementioned scenarios C29/C30 in order to eliminate heat losses through the building envelope. The results show a reduction of the total primary energy consumption of about 69.6% and 70.3% respectively The reduction is quite small ranging between 0.5-1% % because improved windows reduce the solar gains during wintertime.

Cases C36 and C38 examine the contribution of ventilation in the aforementioned scenarios C33 and C34 respectively, which have a more insulated building envelope, and included insulation on the roof, wall, improved windows and heat recovery ventilation, while C35 and C37 consider lower insulation of the wall at 8cm. Again, an increased ventilation rate helps the total energy demand with a 0.5-1% reduction.

Case C39 considers the addition of movable shading device in the aforementioned scenario C33. Although, this retrofitting option improves cooling energy demand, the overall performance improves by just 0.5% leading to a total primary energy consumption reduction of 69.9%.

Case 40 considers the addition of floor insulation in the aforementioned scenario C33. The overall reduction of primary energy consumption reduction is 75.1%.

Cases C41 and C42 considers the advanced retrofitting option incorporating all the examined retrofitting options, examining two different thicknesses of the roof, i.e. 10cm and 15cm. The results show that all the passive strategies can achieve an overall reduction of total primary energy consumption in the range of 76.5- 77.3% respectively.

Figure 15.7 shows the heating and cooling primary energy consumption of combined retrofitting scenarios compared to the reference building of both the first and ground floor south-oriented classroom .

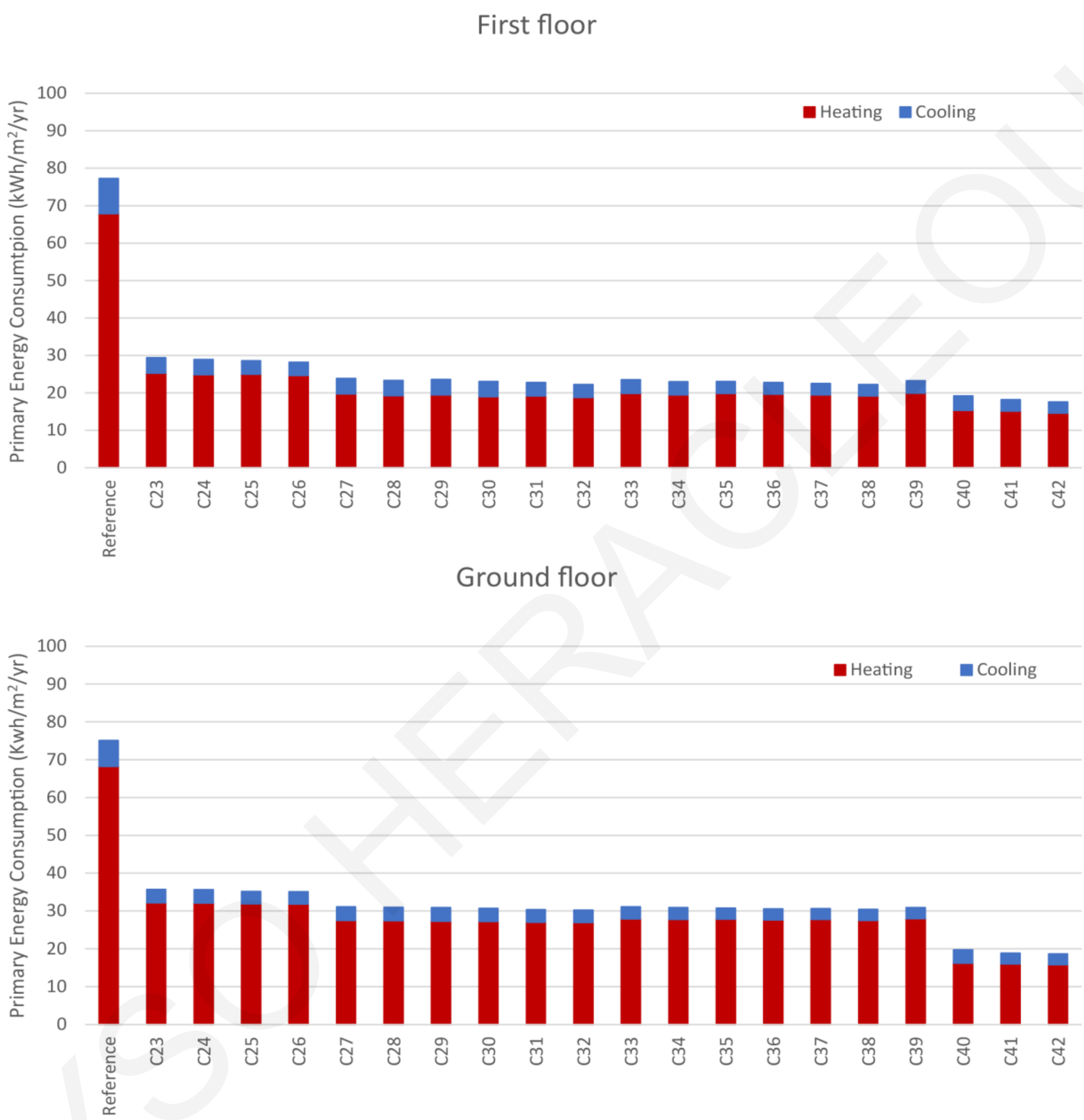



Figure 15.7. Primary energy consumption of the combined retrofitting scenarios during the academic period in the south oriented classroom of the first and ground floor (C23: Roof ins.10 cm +MVHR, C24: Roof ins.15 cm +MVHR, C25:Roof ins.10 cm +MVHR+ Vent, C26: Roof ins.15 cm +MVHR+ Vent, C27: Roof ins.10 cm +MVHR+ Wall ins. 8 cm, C28: Roof ins.15 cm +MVHR+ Wall ins. 8 cm, C29: Roof ins.10 cm +MVHR+ Wall ins. 10 cm, C30: Roof ins.15 cm +MVHR+ Wall ins. 10 cm, C31: Roof ins.10 cm +MVHR+ Wall ins. 10 cm+ Vent, C32: Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Vent, C33: Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame, C34: Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame, C35: Roof ins.10 cm +MVHR+ Wall ins. 8 cm + Double glazed low-e insulated frame+ Vent, C36: Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame+ Vent, C37: Roof ins.15 cm +MVHR+ Wall ins. 8 cm + Double glazed low-e insulated frame+ Vent, C38: Roof ins.15 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame+ Vent, C39: Roof ins.10 cm +MVHR+

Wall ins. 10 cm + Double glazed low-e insulated frame+ Shading, C40: Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double glazed low-e insulated frame + Floor ins. 5cm, C41: Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double-glazed low-e insulated frame + Floor ins. 5cm + Shading + Vent, C42: Roof ins.10 cm +MVHR+ Wall ins. 10 cm + Double-glazed low-e insulated frame + Floor ins. 5cm + Shading + Vent.).

### *15.3.3.1. Cost effectiveness of retrofitting scenarios*

#### *15.3.3.1.1. Individual retrofitting scenarios*

In order to demonstrate properly the energy performance and LCCA of each retrofitting scenario application, the reference building remains as a constant and therefore investigates the individual application type. This allows estimating the influences of individual retrofitting options on the building energy performance and LCC on an equal basis. Table 15.10 shows the energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies for the south-oriented classroom on the first floor.

Table 15.10. Energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies.

| Compo-nent | Scena-rios | Annual Heating Load (MWh) | Annual Cooling Load (MWh) | Annual final cons. (kWh/m²/y) | Annual primary energy (kWh/m²/y) | Total $CO_2$ Emissions (kg$CO_2$/m²/y) | Invest-ment cost (€) | LCCA (€) |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.18 | 1.17 | 65.17 | 77.24 | 25.49 | - | 20,347 |
| **Wall** | C1 | 3.00 | 0.84 | 60.78 | 70.83 | 22.39 | 1,391 | 20,053 |
| | C2 | 2.98 | 0.84 | 60.37 | 70.41 | 22.29 | 1,521 | 20,111 |
| | C3 | 2.97 | 0.84 | 60.22 | 70.24 | 22.25 | 1,619 | 20,180 |
| | C4 | 2.96 | 0.84 | 59.98 | 69.98 | 22.19 | 1,782 | 20,300 |
| **Roof** | C5 | 2.80 | 0.57 | 56.01 | 64.32 | 19.52 | 3,024 | 19,601 |
| | C6 | 2.75 | 0.54 | 55.01 | 63.08 | 19.06 | 3,444 | 19,807 |
| | C7 | 2.73 | 0.53 | 54.61 | 62.58 | 18.88 | 3,864 | 20,147 |
| | C8 | 2.72 | 0.52 | 54.39 | 62.30 | 18.78 | 4,284 | 20,523 |
| **Floor** | C9 | 3.05 | 0.84 | 61.75 | 71.90 | 22.67 | 3,808 | 23,334 |
| | C10 | 3.04 | 0.84 | 61.50 | 71.65 | 22.62 | 3,920 | 23,402 |
| | C11 | 3.03 | 0.84 | 61.40 | 71.54 | 22.60 | 4,088 | 23,552 |
| **Window** | C12 | 3.20 | 0.78 | 64.35 | 74.50 | 23.13 | 3,320 | 21,938 |
| | C13 | 3.19 | 0.77 | 64.16 | 74.25 | 23.02 | 4,150 | 22,729 |
| | C14 | 3.17 | 0.77 | 63.91 | 73.97 | 22.95 | 4,980 | 23,512 |
| | C15 | 3.18 | 0.76 | 64.09 | 74.12 | 22.95 | 5,810 | 24,371 |
| **Ventilation** | C17 | 3.18 | 0.67 | 63.70 | 73.26 | 22.33 | 1,000 | 22,556 |
| | C18 | 3.18 | 0.64 | 63.62 | 73.04 | 22.16 | 1,000 | 22,528 |
| **Shading** | C20 | 3.38 | 0.82 | 67.98 | 78.69 | 24.42 | 1,250 | 23,102 |
| | C21 | 3.18 | 0.76 | 63.99 | 73.99 | 22.89 | 2,175 | 25,910 |
| **MVHR** | C22 | 1.57 | 0.77 | 32.73 | 39.65 | 13.80 | 4,000 | 22,396 |

The **Wall** retrofitting scenarios on Table 15.10 present the four scenarios based on four different thicknesses (5cm to 15cm) of a Rockwool render system thus different U-Value and cost characteristics. As observed, all the cases provide lower LCC ($\Delta Cg$= -0.2-1.4%) for the 30 years of calculation compared to the reference building, making all the retrofitting options to be cost-effective. The higher the insulation, the higher the LCCA, ranging from €20,053 to €20,300. The reduction of primary energy compared to the reference building is about 6-7 kWh/m$^2$/yr.

The **Roof** retrofitting scenarios illustrate calculations for the four different thicknesses of insulation (5cm to 20cm) covered with paving slabs, thus different U-Value and cost characteristics. As shown in Table 15.10, cases up to 15cm insulation provide lower LCC (ΔCg= -1.0-3.7%) for the 30 years of calculations compared to the reference building and the cases of improved wall systems, making the roof retrofitting options to be cost-effective. Although the initial investment cost is higher than the improved wall system, the energy saving is higher. However the case with 20cm roof insulation (C8) shows a higher LCC by 0.9% compared to the reference building. The higher the insulation, the higher the LCCA ranging from €19,601 to €20,523. The reduction of primary energy consumption compared to the reference building is about 13-14 kWh/m$^2$/yr.

The **Floor** retrofitting scenarios present the three different cases of insulation thicknesses (5cm to 10cm) covered by concrete screed and floor tiles, thus different U-Value and cost characteristics. As shown in Table 15.10, all the cases provide higher LCC (ΔCg= 14.7-15.8%) for the 30 years of calculations compared to the reference building. The higher the insulation, the higher the LCCA ranging from €23,334 to €23,552. The reduction of primary energy consumption compared to the reference building is about 5-6 kWh/m$^2$/yr. The investment cost of this strategy is quite high and is considered as an advanced retrofitting option due to its difficulty to construct.

The **Windows** retrofitting scenarios involve four different cases of improved windows with relatively high-performance glazing systems and window frames, thus different U-Value and cost characteristics. As shown in Table 15.10, all the cases provide higher LCCA (ΔCg= 7.9-19.8%) for the 30 years of calculations compared to the reference building. The more advanced window system, the higher the LCCA ranging from €21,938 to €24,371. The reduction of primary energy consumption compared to the reference building is about 3 kWh/m$^2$/yr. Due to the fact that the investment cost is considered quite high compared to the impact on energy saving, windows alone do not seem to be such a cost-effective strategy for educational buildings.

**Ventilation** retrofitting scenarios present the two cases of different natural ventilation, one with night cooling and a great ventilation rate during daytime, and one with night ventilation alone. As shown in Table 15.10, all the cases provide higher LCCA for the 30 years of calculations compared to the reference building. The case of night ventilation alone provides slightly better LCC compared to the case of additional ventilation during daytime due to the lower energy needs. Specifically, night ventilation alone has an LCC of €22,556 (ΔCg= 10.9%), while night ventilation associated with extra ventilation during daytime has an LLC of €22,528 (ΔCg= 10.8%). The reduction of primary energy consumption compared to the reference building is about 4 kWh/m$^2$/yr.

**Shading** retrofitting scenarios present the two cases of two different shading elements for the south-oriented classroom, one with fixed shading using louvers and one with movable shading using louvers. The case of fixed shading provides a higher LLC and higher energy needs compared to the reference building and thus is not considered as a cost-effective strategy. The movable shading provides a higher LCC for the 30 years of calculations compared to the reference building, i.e. €25,910 (ΔCg= 27.3%). The reduction of primary energy consumption compared to the reference building is about 3 kWh/m$^2$/yr. Due to the fact that the south-oriented classroom is shaded from the existing overhang used as corridor, the additional shading system alone does not seem to be a cost-effective strategy for south-facing classrooms. It has to be taken into consideration that for classrooms with other orientations, such as east or west, the impact of shading systems on energy performance and LCC may be differentiated, as these classrooms do not incorporate the appropriate shading system.

The **MVHR** retrofitting option is deemed important for both thermal comfort and air quality. The case of MVHR provides higher LCC for the 30 years of calculations compared to the reference building, i.e. €22,396 (ΔCg= 10.1%). However, the reduction of primary energy consumption compared to the reference building is quite high at about 38 kWh/m$^2$/yr.

Figure 15.7 shows the LCCA of individual retrofit approaches according to different characteristics. The curve represents a theoretical set of optimal solutions by considering the reference building as a starting point. As shown, the application of roof insulation has the lowest cost with a significant reduction in energy consumption compared to the reference building.

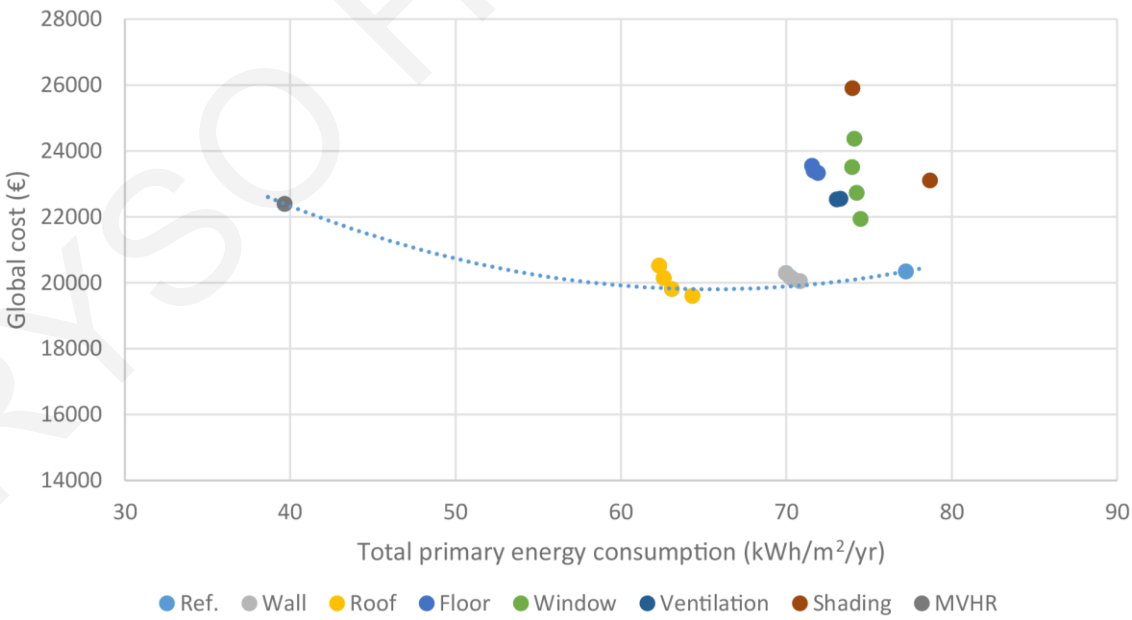



Figure 15.8. Cost optimality study-comparison for different individual retrofitting scenarios.

*15.3.3.1.2. Combinations of retrofitting scenarios*

Having considered the previous individual investigations, the final optimum retrofit scenario for this building is determined using some combinations. In order to minimize the cases for the whole building optimization, some subjects remain constant, by using the optimal case from previous examinations, especially for the construction interventions. Specifically, the two best cases of wall, roof as well as the best case of floor insulation were investigated combined with other strategies, setting up 20 scenarios. It has to be noted that all combinations aimed to satisfy the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020 onwards. Combinations considered light, mild and advanced retrofitting scenarios, based on the ability to reduce the energy consumption as well as on the difficulty of application. Table 15.11 tabulates the energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies for the south-oriented classroom on the first floor.

Table 15.11. Energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies.

| **Strategy Combination** | **Scenarios** | **Annual Heating Load (MWh)** | **Annual Cooling Load (MWh)** | **Annual final cons. (kWh/m$^2$/yr)** | **Annual primary energy (kWh/m$^2$/yr)** | **Total $CO_2$ Emissions $kgCO_2$/m$^2$/y** | **Invest-ment cost (€)** | **LCCA (€)** |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.18 | 1.17 | 65.17 | 77.24 | 25.49 | - | 20,347 |
| **Roof10cm +MVHR** | C23 | 1.18 | 0.51 | 24.49 | 29.38 | 9.99 | 7,444 | 22,413 |
| **Roof15cm +MVHR** | C24 | 1.17 | 0.50 | 24.12 | 28.93 | 9.82 | 7,864 | 23,849 |
| **Roof10cm +MVHR+ Vent** | C25 | 1.17 | 0.45 | 24.07 | 28.61 | 9.51 | 8,444 | 25,050 |
| **Roof15cm +MVHR+ Vent** | C26 | 1.15 | 0.44 | 23.71 | 28.17 | 9.35 | 8,864 | 25,398 |
| **Roof10cm +MVHR+ Wall8cm** | C27 | 0.92 | 0.51 | 19.47 | 23.86 | 8.53 | 8,965 | 23,389 |
| **Roof15cm +MVHR+ Wall8cm** | C28 | 0.90 | 0.50 | 19.02 | 23.31 | 8.33 | 9,385 | 23,719 |
| **Roof10cm +MVHR+ Wall10cm** | C29 | 0.91 | 0.51 | 19.23 | 23.60 | 8.46 | 9,063 | 22,352 |
| **Roof 15cm+MVHR+ Wall10cm** | C30 | 0.89 | 0.50 | 18.77 | 23.03 | 8.25 | 9,483 | 22,681 |
| **Roof10cm +MVHR+ Wall10cm+Vent** | C31 | 0.90 | 0.45 | 18.80 | 22.80 | 7.96 | 10,063 | 24,987 |
| **Roof15cm +MVHR+ Wall10cm+Vent** | C32 | 0.88 | 0.44 | 18.35 | 22.26 | 7.77 | 10,483 | 25,318 |
| **Roof10cm +MVHR+ Wall10cm+Window** | C33 | 0.93 | 0.45 | 19.42 | 23.52 | 8.18 | 14,043 | 25,975 |
| **Roof15cm +MVHR+ Wall10cm+Window** | C34 | 0.91 | 0.44 | 18.97 | 22.96 | 7.97 | 14,463 | 26,306 |
| **Roof10cm +MVHR+ Wall8cm+Wind.+Vent** | C35 | 0.93 | 0.39 | 19.26 | 23.05 | 7.80 | 14,945 | 28,565 |
| **Roof10cm +MVHR+ Wall10cm+Wind.+Vent** | C36 | 0.92 | 0.39 | 19.01 | 22.78 | 7.72 | 15,043 | 28,617 |
| **Roof15cm +MVHR+ Wall8cm+Wind.+Vent** | C37 | 0.91 | 3.07 | 26.83 | 44.13 | 24.77 | 15,365 | 28,899 |
| **Roof15cm +MVHR+ Wall10cm+Wind.+Vent** | C38 | 0.90 | 0.38 | 18.57 | 22.24 | 7.53 | 15,463 | 28,951 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Shading** | C39 | 0.93 | 0.41 | 19.33 | 23.22 | 7.92 | 16,218 | 31,606 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Floor5cm** | C40 | 0.72 | 0.48 | 15.39 | 19.21 | 7.14 | 17,851 | 29,909 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Roof 10cm+MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C41 | 0.71 | 0.38 | 14.89 | 18.17 | 6.43 | 21,026 | 37,325 |
| **Roof15cm +MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C42 | 0.68 | 0.36 | 14.38 | 17.56 | 6.22 | 21,446 | 37,465 |

All cases include MVHR, as it is important for both air quality but also for thermal and energy performance in educational buildings. The MVHR decreases the heat loss from ventilation dramatically during winter, and hence the hours of discomfort, as it provides controlled ventilation and ensures the required air exchange in order to maintain indoor air quality. During the summer period, it removes the warm air to the outside thus cooling the building envelope. Additionally, with the recent global spread of the Covid-19 virus, educational buildings have become central to both global and local efforts of controlling the pandemic, making the provision of fresh air throughout the entire academic year  not only an ideal situation to achieve in the future, but a crucial and vital necessity.

Scenarios C23-C24 combine the most effective cases in terms of energy saving, i.e. MVHR and roof insulation 10cm and 15cm thick. As observed, with an increase of 10% and 17% of the LCC compared to the reference building, the primary energy consumption is reduced by 47-48 kWh/m$^2$/year respectively. The LCC is €22,413 and €23,849 respectively.

Scenarios C25-C26 consider additional ventilation during daytime and nigh time in order to investigate its cost-effectiveness. As observed, with an increase of 23-25% of the LCC compared to the reference building, the primary energy consumption is marginally reduced (1%) compared to the previous scenarios, i.e. 48-49 kWh/m2/year reduction compared to the reference building. The LCC ranges from €25,050 to €25,398. The results show that a ventilation of 1000 l/s is not necessary during daytime and night time if the MVHR is already installed.

Scenarios C27-C30 investigate the two best scenarios of wall and roof insulation in terms of the LCC, and indicate which case provides the best LCC when it is combined with the MVHR. The best-case scenario is the one with the 10cm insulation on the roof and the 10cm insulation on the wall, in combination with the MVHR (C29), giving the lowest LCC at €22,352. The results show that primary energy consumption is reduced by 54 kWh/m$^2$/year for 10% increase of LCC compared to the reference building. Here it is worth mentioning that although the investment cost is higher compared to the aforementioned cases, the reduction of primary energy consumption offsets this difference. Moreover, as the numbers indicate, a 10cm wall insulation works better in terms of lower LCC and energy saving compared to the wall with 8cm insulation. Additionally, the difference between 10cm and 15cm of insulation on the roof has a minor difference regarding the LCC and therefore the best in terms of performance (i.e. 15cm insulation) can be used. However, for each combination the analysis presents data for both two cases in order to have an overview of the performance for both cases.

Scenarios C31-C32 again include additional ventilation to the one in the aforementioned C29-C30 scenarios in order to identify whether it has a higher impact on a more insulated building envelope. Again, the energy performance of these scenarios is only 1% lower compared to the C29-C30 scenarios. The LCC is about 23-24% higher than the reference building ranging from €24,987 to €25,318 with a total reduction of primary energy of about 54-55 kWh/m$^2$/year.

Scenarios C33-C34 include improved windows to the ones in scenarios C29-C30 in order to achieve an optimally insulated building envelope, avoiding condensation. It is worth mentioning that in order to be compatible with the Law and the minimum requirements set therein, the double low-e with insulated frame window system was selected for analysis. It has to be noted that with an increase of 28-29% of the LCC (€25,975 - €26,306) compared to the reference building, a reduction of primary energy consumptions is minor compared to scenarios C29-C30 that do not include window replacement, i.e. only 0.2 kWh/m$^2$/year compared to C29-C30. Again, the combinations showed that windows are not a cost-effective solution.

Scenarios C35-C38 examine the addition of ventilation to the aforementioned cases C33-C34 but also examine the performance of different insulation thicknesses on the wall. The results showed an increase of the LCC by about 40-42% compared to the reference building, i.e. €28,565- €28,951 with a reduction of primary energy consumption by 54-55 kWh/m$^2$/year.

The C39 scenario examines the impact of adding shading devices to the aforementioned C33 scenario, both in terms of energy performance and LCC. The results showed an increase of the LCC by about 55% compared to the reference building, i.e. €31,606 with a reduction of primary energy consumption by 62-54 kWh/m$^2$/year. Again, the combinations show that a shading system in the south-oriented classroom is not necessary nor cost-effective.

The C40 scenario investigates the addition of insulation on the ground floor to the aforementioned scenario C33. The results show an increase of the LCC by about 47% compared to the reference building, i.e. €29,909 with a reduction of primary energy consumption by 58 kWh/m$^2$/year.

Scenarios C41-C42 combine all the examined types of retrofit with different roof insulation in order to achieve the maximum energy performance and to identify the impact on the LCC. The results showed an increase of the LCC by about 83-84% compared to the reference building, i.e. €37,325 and €37,465 with a reduction of primary energy consumption by 59-60 kWh/m$^2$/year. This shows that the advance retrofitting scenario is not a cost-effective solution for the improvement of energy performance of educational buildings.

Figure 15.8 shows the LCCA of combined retrofit approaches according to different characteristics. The curve represents a theoretical set of optimal solutions by considering the reference building as a starting point. As shown, the application of roof insulation in combination with the addition of MVHR and wall insulation has the lowest cost with a significant reduction in energy consumption compared to the reference building. The purpose of this chart is to develop some guidelines to select suitable retrofitting measures for educational buildings.

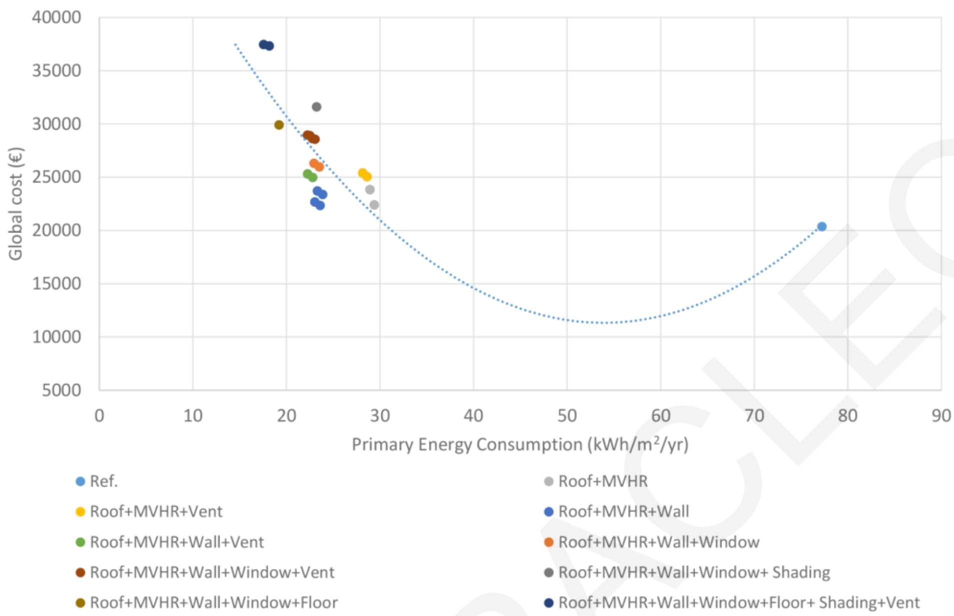



Figure 15.9. Cost optimality study-comparison for different combined retrofitting scenarios.

### *15.3.4. Sensitivity analysis of adaptation measures*

The sensitivity analysis considered different values in discount rate and energy prices in order to identify the robustness of key input parameters which can help the development of recommendations for decision makers. Additionally, in the framework of a holistic retrofitting approach, the life cycle cost of adaptation measures was examined in the framework of all-day use of schools for other activities in order to identify how the schedule of a building affects the results.

#### *15.3.4.1. Discount rate at 3%*

Figure 15.10 shows the results achieved for a discount rate fixed to 3% for the individual retrofitting scenarios, while Figure 15.11 shows the results for the combinations. Table 15.12 shows the energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies while Table 15.13 shows the energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies under the fixed discount rate of 3%.

As shown, a higher interest rate lead to a decrease of the global cost both for the reference as well as for the proposed retrofitting options. The LCC of the reference building is €14,246. In terms of the individual retrofitting options, all wall-retrofitting scenarios provide higher LCC compared to the reference building by 1.4-3.5%. In terms of the roof-retrofitting scenarios, all roof-retrofitting scenarios provide higher LCC compared to the reference building by 2.5-9.8%. Floor-retrofitting scenarios provide higher LCC by 22.8-24.5% compared to the reference building. Window-retrofitting scenarios provide higher LCC by 14.7-31.9% compared to the reference building.

Ventilator-retrofitting scenarios provide higher LCC by 13-13.1% compared to the reference building. Shading-retrofitting scenarios provide higher LCC by 16.3-32.4% compared to the reference building. The MVHR-retrofitting scenario provides higher LCC by 19.8% compared to the reference building. All individual strategies provide higher LCC compared to the reference building.

Table 15.12. Energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies for discount rate of 3%.

| Compo-nent | Scena-rios | Annual Heating Load (MWh) | Annual Cooling Load (MWh) | Annual final cons. ($kWh/m^2/y$) | Annual primary energy ($kWh/m^2/y$) | Total $CO_2$ Emissions ($kgCO_2/m^2/y$) | Invest-ment cost (€) | LCCA (€) |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.18 | 1.17 | 65.17 | 77.24 | 25.49 | - | 14,246 |
| **Wall** | C1 | 3.00 | 0.84 | 60.78 | 70.83 | 22.39 | 1,391 | 14,448 |
| | C2 | 2.98 | 0.84 | 60.37 | 70.41 | 22.29 | 1,521 | 14,529 |
| | C3 | 2.97 | 0.84 | 60.22 | 70.24 | 22.25 | 1,619 | 14,607 |
| | C4 | 2.96 | 0.84 | 59.98 | 69.98 | 22.19 | 1,782 | 14,741 |
| **Roof** | C5 | 2.80 | 0.57 | 56.01 | 64.32 | 19.52 | 3,024 | 14,599 |
| | C6 | 2.75 | 0.54 | 55.01 | 63.08 | 19.06 | 3,444 | 14,880 |
| | C7 | 2.73 | 0.53 | 54.61 | 62.58 | 18.88 | 3,864 | 15,245 |
| | C8 | 2.72 | 0.52 | 54.39 | 62.30 | 18.78 | 4,284 | 15,635 |
| **Floor** | C9 | 3.05 | 0.84 | 61.75 | 71.90 | 22.67 | 3,808 | 17,494 |
| | C10 | 3.04 | 0.84 | 61.50 | 71.65 | 22.62 | 3,920 | 17,575 |
| | C11 | 3.03 | 0.84 | 61.40 | 71.54 | 22.60 | 4,088 | 17,731 |
| **Window** | C12 | 3.20 | 0.78 | 64.35 | 74.50 | 23.13 | 3,320 | 16,334 |
| | C13 | 3.19 | 0.77 | 64.16 | 74.25 | 23.02 | 4,150 | 17,137 |
| | C14 | 3.17 | 0.77 | 63.91 | 73.97 | 22.95 | 4,980 | 17,935 |
| | C15 | 3.18 | 0.76 | 64.09 | 74.12 | 22.95 | 5,810 | 18,785 |
| **Ventilation** | C17 | 3.18 | 0.67 | 63.70 | 73.26 | 22.33 | 1,000 | 16,115 |
| | C18 | 3.18 | 0.64 | 63.62 | 73.04 | 22.16 | 1,000 | 16,096 |
| **Shading** | C20 | 3.38 | 0.82 | 67.98 | 78.69 | 24.42 | 1,250 | 16,574 |
| | C21 | 3.18 | 0.76 | 63.99 | 73.99 | 22.89 | 2,175 | 18,868 |
| **MVHR** | C22 | 1.57 | 0.77 | 32.73 | 39.65 | 13.80 | 4,000 | 17,071 |

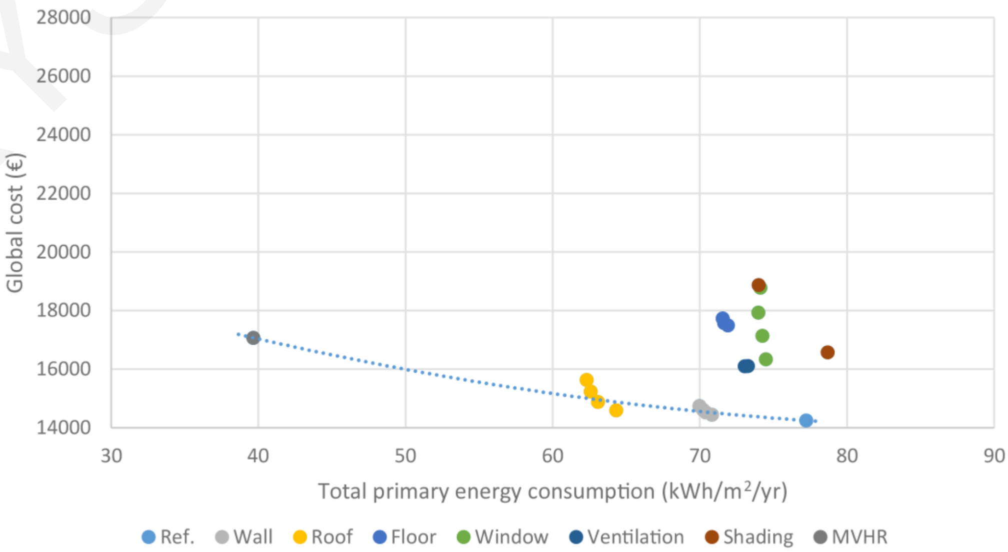


Figure 15.10. Cost optimality study-comparison for different individual retrofitting scenarios for a fixed discount rate of 3%.

In terms of the combinations, the lowest LCC compared to the reference building is provided by case C23 where the MVHR in combination with 10cm of insulation on the roof were applied. The LCC of C23 is about 27% higher compared to the reference building. The second lowest LCC is for the scenario where the MVHR, a 10cm of insulation on the roof and a 10cm of insulation on the wall were applied (i.e. C29) followed by the case where the MVHR, 15 cm of insulation on the roof and 10cm of insulation on the wall were applied (i.e. C30). The LCC of C29 and C30 is higher by 30% and 33% respectively compared to the reference building. Additional ventilation in the C29 scenario, i.e. C31 provides an increase of the LCC by 45%. All the other strategies seem to stray too far from the reference and thus are not considered as cost-effective.

Table 15.13. Energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies for discount rate of 3%.

| **Strategy Combination** | **Scenarios** | **Annual Heating Load (MWh)** | **Annual Cooling Load (MWh)** | **Annual final cons. (kWh/m$^2$/yr)** | **Annual primary energy (kWh/m$^2$/yr)** | **Total $CO_2$ Emissions $kgCO_2/m^2/y$** | **Invest-ment cost (€)** | **LCCA (€)** |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.18 | 1.17 | 65.17 | 77.24 | 25.49 | - | 14,246 |
| **Roof10cm +MVHR** | C23 | 1.18 | 0.51 | 24.49 | 29.38 | 9.99 | 7,444 | 18,083 |
| **Roof15cm +MVHR** | C24 | 1.17 | 0.50 | 24.12 | 28.93 | 9.82 | 7,864 | 19,237 |
| **Roof10cm +MVHR+ Vent** | C25 | 1.17 | 0.45 | 24.07 | 28.61 | 9.51 | 8,444 | 20,243 |
| **Roof15cm +MVHR+ Vent** | C26 | 1.15 | 0.44 | 23.71 | 28.17 | 9.35 | 8,864 | 20,614 |
| **Roof10cm +MVHR+ Wall8cm** | C27 | 0.92 | 0.51 | 19.47 | 23.86 | 8.53 | 8,965 | 19,239 |
| **Roof15cm +MVHR+ Wall8cm** | C28 | 0.90 | 0.50 | 19.02 | 23.31 | 8.33 | 9,385 | 19,597 |
| **Roof10cm +MVHR+ Wall10cm** | C29 | 0.91 | 0.51 | 19.23 | 23.60 | 8.46 | 9,063 | 18,522 |
| **Roof 15cm+MVHR+ Wall10cm** | C30 | 0.89 | 0.50 | 18.77 | 23.03 | 8.25 | 9,483 | 18,879 |
| **Roof10cm +MVHR+ Wall10cm+Vent** | C31 | 0.90 | 0.45 | 18.80 | 22.80 | 7.96 | 10,063 | 20,680 |
| **Roof15cm +MVHR+ Wall10cm+Vent** | C32 | 0.88 | 0.44 | 18.35 | 22.26 | 7.77 | 10,483 | 21,040 |
| **Roof10cm +MVHR+ Wall10cm+Window** | C33 | 0.93 | 0.45 | 19.42 | 23.52 | 8.18 | 14,043 | 22,525 |
| **Roof15cm +MVHR+ Wall10cm+Window** | C34 | 0.91 | 0.44 | 18.97 | 22.96 | 7.97 | 14,463 | 22,883 |
| **Roof10cm +MVHR+ Wall8cm+Wind.+ Vent** | C35 | 0.93 | 0.39 | 19.26 | 23.05 | 7.80 | 14,945 | 24,621 |
| **Roof10cm +MVHR+ Wall10cm+Wind.+ Vent** | C36 | 0.92 | 0.39 | 19.01 | 22.78 | 7.72 | 15,043 | 24,688 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Roof15cm +MVHR+ Wall8cm+Wind.+ Vent** | C37 | 0.91 | 0.38 | 18.82 | 22.52 | 7.61 | 15,365 | 24,983 |
| **Roof15cm +MVHR+ Wall10cm+Wind.+ Vent** | C38 | 0.90 | 0.38 | 18.57 | 22.24 | 7.53 | 15,463 | 25,049 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Shading** | C39 | 0.93 | 0.41 | 19.33 | 23.22 | 7.92 | 16,218 | 27,198 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Floor5cm** | C40 | 0.72 | 0.48 | 15.39 | 19.21 | 7.14 | 17,851 | 26,432 |
| **Roof 10cm+MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C41 | 0.71 | 0.38 | 14.89 | 18.17 | 6.43 | 21,026 | 32,670 |
| **Roof15cm +MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C42 | 0.68 | 0.36 | 14.38 | 17.56 | 6.22 | 21,446 | 32,896 |

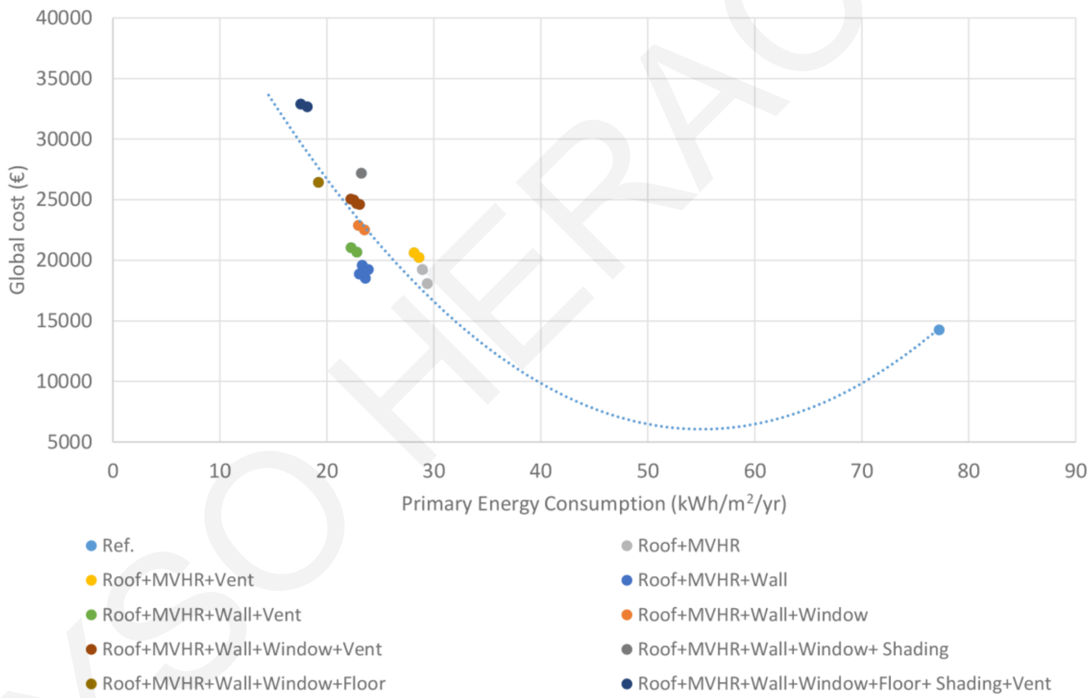



Figure 15.11. Cost optimality study-comparison for different combined retrofitting scenarios for a fixed discount rate of 3%.

*15.3.4.2. Increase in the rate of increase of energy price*

The second part of the sensitivity analysis considered a different **rate of increase of the energy price.**

The first case considered an additional increase of 0.5% in a rate of increase per year as a projection to the future for both the electricity and heating oil price (i.e. 2.7% increase of electricity and 4.3% increase of heating oil price) for the first case.

A higher development of energy price supports the selection of the solutions characterized by the lower energy demands. The increase of energy price leads to a higher LCC of the reference building and a reduced LCC of the retrofitting interventions. Figure 15.12 shows the results achieved by an additional increase of 0.5% of the energy price for the individual retrofitting scenarios, while Figure 15.13 shows the results for the combinations. Table 15.14 shows the energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies while Table 15.15 shows the energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies under the increase of energy price.

The LCC of the reference building is €21,390. In terms of the individual retrofitting options, all wall-retrofitting scenarios provide lower LCC compared to the reference building by 0.7-1.8%. In terms of the roof-retrofitting scenarios, again all cases provide lower LCC compared to the reference building by about 0.1-4.3%. Floor-retrofitting scenarios provide higher LCC by 13.7-14.7% compared to the reference building. Window-retrofitting scenarios provide higher LCC by 7.3-18.7% compared to the reference building. Ventilation-retrofitting scenarios provide higher LCC by 10.0-10.1% compared to the reference building. Shading-retrofitting scenarios provide higher LCC by 13.0-25.9% compared to the reference building. The MVHR-retrofitting scenario provides higher LCC by 7.2% compared to the reference building. The lowest cost of an individual set of strategies is around €20,671 and concerns the 10cm of roof insulation.

Table 15.14. Energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies for additional increase of 0.5% in the rate of increase on the energy price.

| **Compo-nent** | **Scena-rios** | **Annual Heating Load (MWh)** | **Annual Cooling Load (MWh)** | **Annual final cons. (kWh/m$^2$/y)** | **Annual primary energy (kWh/m$^2$/y)** | **Total $CO_2$ Emissions ($kgCO_2/m^2/y$)** | **Invest-ment cost (€)** | **LCCA (€)** |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.18 | 1.17 | 65.17 | 77.24 | 25.49 | - | 21,390 |
| **Wall** | C1 | 3.00 | 0.84 | 60.78 | 70.83 | 22.39 | 1,391 | 21,016 |
| | C2 | 2.98 | 0.84 | 60.37 | 70.41 | 22.29 | 1,521 | 21,068 |
| | C3 | 2.97 | 0.84 | 60.22 | 70.24 | 22.25 | 1,619 | 21,135 |
| | C4 | 2.96 | 0.84 | 59.98 | 69.98 | 22.19 | 1,782 | 21,251 |
| **Roof** | C5 | 2.80 | 0.57 | 56.01 | 64.32 | 19.52 | 3,024 | 20,482 |
| | C6 | 2.75 | 0.54 | 55.01 | 63.08 | 19.06 | 3,444 | 20,671 |
| | C7 | 2.73 | 0.53 | 54.61 | 62.58 | 18.88 | 3,864 | 21,004 |
| | C8 | 2.72 | 0.52 | 54.39 | 62.30 | 18.78 | 4,284 | 21,377 |
| **Floor** | C9 | 3.05 | 0.84 | 61.75 | 71.90 | 22.67 | 3,808 | 24,312 |
| | C10 | 3.04 | 0.84 | 61.50 | 71.65 | 22.62 | 3,920 | 24,376 |
| | C11 | 3.03 | 0.84 | 61.40 | 71.54 | 22.60 | 4,088 | 24,525 |
| **Window** | C12 | 3.20 | 0.78 | 64.35 | 74.50 | 23.13 | 3,320 | 22,954 |
| | C13 | 3.19 | 0.77 | 64.16 | 74.25 | 23.02 | 4,150 | 23,742 |
| | C14 | 3.17 | 0.77 | 63.91 | 73.97 | 22.95 | 4,980 | 24,521 |
| | C15 | 3.18 | 0.76 | 64.09 | 74.12 | 22.95 | 5,810 | 25,382 |
| **Ventilation** | C17 | 3.18 | 0.67 | 63.70 | 73.26 | 22.33 | 1,000 | 23,558 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | C18 | 3.18 | 0.64 | 63.62 | 73.04 | 22.16 | 1,000 | 23,528 |
| **Shading** | C20 | 3.38 | 0.82 | 67.98 | 78.69 | 24.42 | 1,250 | 24,175 |
| | C21 | 3.18 | 0.76 | 63.99 | 73.99 | 22.89 | 2,175 | 26,919 |
| **MVHR** | C22 | 1.57 | 0.77 | 32.73 | 39.65 | 13.80 | 4,000 | 22,926 |

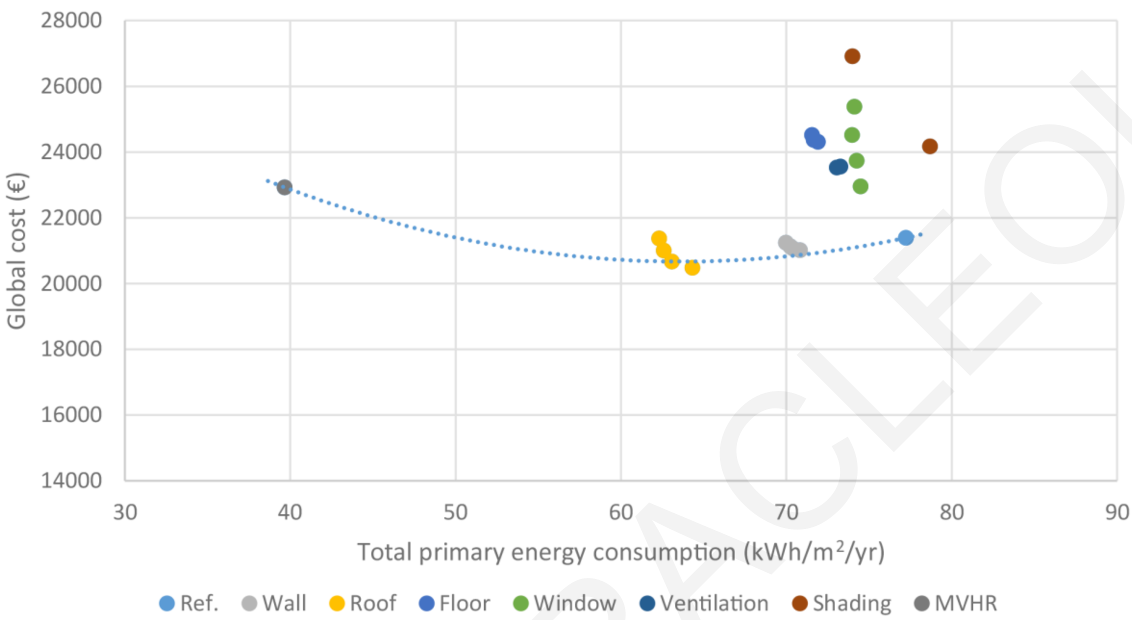



Figure 15.12. Cost optimality study-comparison for different individual retrofitting scenarios for an additional increase of 0.5% in the rate of increase on the energy price.

In terms of the combinations, the lowest LCC compared to the reference building was provided by the case C29 where MVHR in combination with 10cm of insulation on the roof and 10cm of insulation on the wall were applied. The LCC of scenario C29 is about 6% higher compared to the reference building; providing however, a 69% reduction of the primary energy consumption compared to the reference building. The second lowest LCC is provided by the scenario where the MVHR, 15 cm of insulation on the roof and 10cm of insulation on the wall were applied (i.e. C30). The LCC of C30 was higher by about 7% compared to the reference building. Additional ventilation to scenario C29, i.e. C31 provided an increase of the LCC by 18% and a decrease of primary energy consumption by 70%. Improved building envelope by adding high performance windows to scenario C29, i.e. C33, provided an increase of the LCC by 23% and a decrease of primary energy consumption by 70%. Again, the reduction of primary energy consumption is not significant in order to be considered as a cost-effective solution.

Table 15.15. Energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies for additional increase of 0.5% in the rate of increase on the energy price.

| **Strategy Combination** | **Scenarios** | **Annual Heating Load (MWh)** | **Annual Cooling Load (MWh)** | **Annual final cons. (kWh/ $m^2$/yr)** | **Annual primary energy (kWh/ $m^2$/yr)** | **Total $CO_2$ Emissi-ons $kgCO_2/m^2/y$** | **Invest-ment cost (€)** | **LCCA (€)** |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.18 | 1.17 | 65.17 | 77.24 | 25.49 | - | 21,390 |
| **Roof10cm +MVHR** | C23 | 1.18 | 0.51 | 24.49 | 29.38 | 9.99 | 7,444 | 22,807 |
| **Roof15cm +MVHR** | C24 | 1.17 | 0.50 | 24.12 | 28.93 | 9.82 | 7,864 | 24,237 |
| **Roof10cm +MVHR+ Vent** | C25 | 1.17 | 0.45 | 24.07 | 28.61 | 9.51 | 8,444 | 25,435 |
| **Roof15cm +MVHR+ Vent** | C26 | 1.15 | 0.44 | 23.71 | 28.17 | 9.35 | 8,864 | 25,778 |
| **Roof10cm +MVHR+ Wall8cm** | C27 | 0.92 | 0.51 | 19.47 | 23.86 | 8.53 | 8,965 | 23,706 |
| **Roof15cm +MVHR+ Wall8cm** | C28 | 0.90 | 0.50 | 19.02 | 23.31 | 8.33 | 9,385 | 24,029 |
| **Roof10cm +MVHR+ Wall10cm** | C29 | 0.91 | 0.51 | 19.23 | 23.60 | 8.46 | 9,063 | 22,666 |
| **Roof 15cm+MVHR+ Wall10cm** | C30 | 0.89 | 0.50 | 18.77 | 23.03 | 8.25 | 9,483 | 22,987 |
| **Roof10cm +MVHR+ Wall10cm+Vent** | C31 | 0.90 | 0.45 | 18.80 | 22.80 | 7.96 | 10,063 | 25,292 |
| **Roof15cm +MVHR+ Wall10cm+Vent** | C32 | 0.88 | 0.44 | 18.35 | 22.26 | 7.77 | 10,483 | 25,616 |
| **Roof10cm +MVHR+ Wall10cm+Window** | C33 | 0.93 | 0.45 | 19.42 | 23.52 | 8.18 | 14,043 | 26,290 |
| **Roof15cm +MVHR+ Wall10cm+Window** | C34 | 0.91 | 0.44 | 18.97 | 22.96 | 7.97 | 14,463 | 26,613 |
| **Roof10cm +MVHR+ Wall8cm+Wind.+ Vent** | C35 | 0.93 | 0.39 | 19.26 | 23.05 | 7.80 | 14,945 | 28,875 |
| **Roof10cm +MVHR+ Wall10cm+Wind.+ Vent** | C36 | 0.92 | 0.39 | 19.01 | 22.78 | 7.72 | 15,043 | 28,923 |
| **Roof15cm +MVHR+ Wall8cm+Wind.+ Vent** | C37 | 0.91 | 0.38 | 18.82 | 22.52 | 7.61 | 15,365 | 29,202 |
| **Roof15cm +MVHR+ Wall10cm+Wind.+ Vent** | C38 | 0.90 | 0.38 | 18.57 | 22.24 | 7.53 | 15,463 | 29,250 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Shading** | C39 | 0.93 | 0.41 | 19.33 | 23.22 | 7.92 | 16,218 | 31,918 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Floor5cm** | C40 | 0.72 | 0.48 | 15.39 | 19.21 | 7.14 | 17,851 | 30,231 |
| **Roof 10cm+MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C41 | 0.71 | 0.38 | 14.89 | 18.17 | 6.43 | 21,026 | 37,567 |
| **Roof15cm +MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C42 | 0.77 | 0.43 | 16.27 | 19.94 | 7.12 | 21,446 | 37,699 |

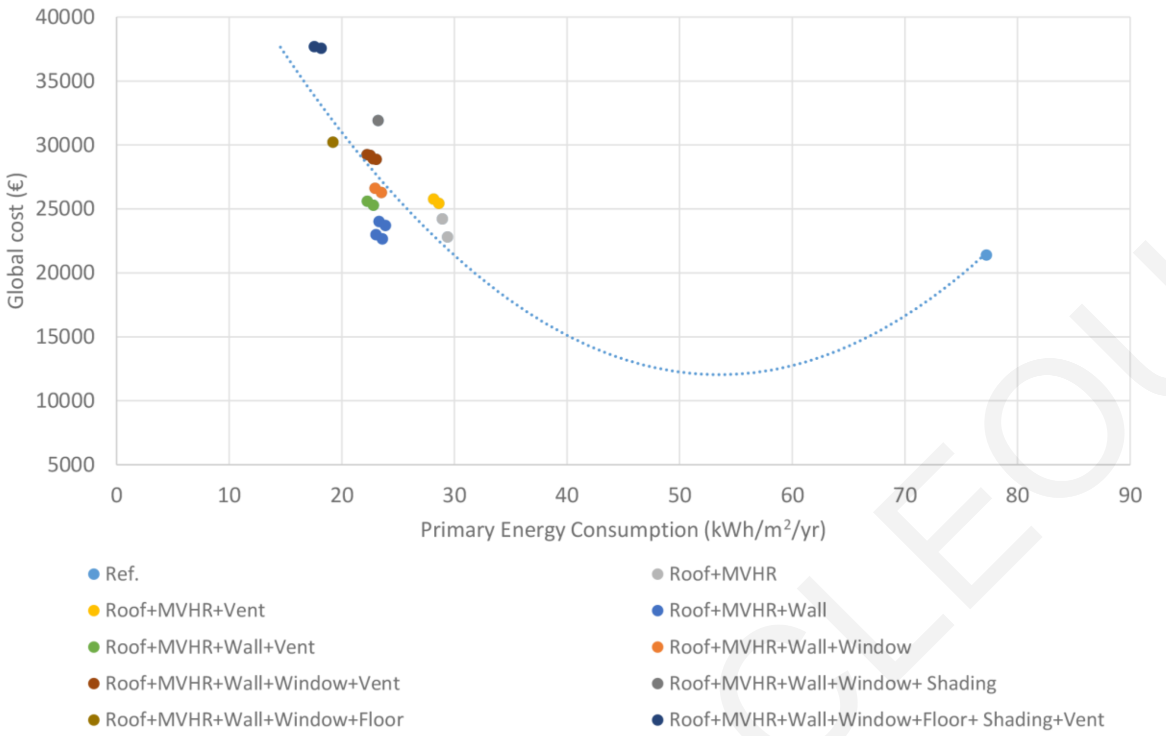



Figure 15.13. Cost optimality study-comparison for different combined retrofitting scenarios for an additional increase of 0.5% in the re rate of increase on the energy price.

*15.3.4.3. Decrease in the rate of increase of energy price*

The second case examined **a small decrease of 0.5% in the rate of increase of the energy price** for energy price (i.e. an increase of 1.7% of electricity and an increase of 3.3% of heating oil).

A lower development of energy price reduced the LCC of the reference building as well as of the retrofit interventions. As the rate of energy price is decreased, the interventions have lower value. Figure 15.14 shows the results achieved for a decrease of 0.5% of the increase of the energy price per year for the individual retrofitting scenarios, while Figure 15.15 shows the results for the combinations. Table 15.16 shows the energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies while Table 15.17 shows the energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies under a decrease of the increase of energy price per year.

The LCC of the reference building is €19,399. In terms of the individual retrofitting options, wall-retrofitting scenarios with 5cm, 8cm and 10cm insulation still provide lower LCC compared to the reference building by 0.5-1.1%; while wall insulation of 15cm thick provides higher LCC by 0.2%. In terms of the roof-retrofitting scenarios, cases with 5cm, 10cm and 15cm insulation provide lower LCC compared to the reference building by 0.2-3.1%; while roof insulation with 20cm provides higher LCC compared to the reference building by 1.8%. Floor-retrofitting scenarios provide higher LCC by 15.8-16.9% compared to the reference building. Window-retrofitting scenarios provided higher LCC by 8.3-20.9% compared to the reference building. Ventilation-retrofitting scenarios provide higher LCC by 11.5% compared to the reference building. Shading-retrofitting scenarios provide higher LCC by 14.1-28.9% compared to the reference building. The MVHR-retrofitting scenario provides higher LCC by 13% compared to the reference building. The lowest cost of an individual set of strategies is around €19,022 and concerns the 10cm of roof insulation.

Table 15.16. Energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies for a decrease of 0.5% in the rate of increase of the energy price.

| Compo-nent | Scena-rios | Annual Heating Load (MWh) | Annual Cooling Load (MWh) | Annual final cons. (kWh/m²/y) | Annual primary energy (kWh/m²/y) | Total $CO_2$ Emissions (kg$CO_2$/m²/y) | Invest-ment cost (€) | LCCA (€) |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.18 | 1.17 | 65.17 | 77.24 | 25.49 | - | 19,399 |
| **Wall** | C1 | 3.00 | 0.84 | 60.78 | 70.83 | 22.39 | 1,391 | 19,177 |
| | C2 | 2.98 | 0.84 | 60.37 | 70.41 | 22.29 | 1,521 | 19,241 |
| | C3 | 2.97 | 0.84 | 60.22 | 70.24 | 22.25 | 1,619 | 19,312 |
| | C4 | 2.96 | 0.84 | 59.98 | 69.98 | 22.19 | 1,782 | 19,435 |
| **Roof** | C5 | 2.80 | 0.57 | 56.01 | 64.32 | 19.52 | 3,024 | 18,801 |
| | C6 | 2.75 | 0.54 | 55.01 | 63.08 | 19.06 | 3,444 | 19,022 |
| | C7 | 2.73 | 0.53 | 54.61 | 62.58 | 18.88 | 3,864 | 19,368 |
| | C8 | 2.72 | 0.52 | 54.39 | 62.30 | 18.78 | 4,284 | 19,747 |
| **Floor** | C9 | 3.05 | 0.84 | 61.75 | 71.90 | 22.67 | 3,808 | 22,445 |
| | C10 | 3.04 | 0.84 | 61.50 | 71.65 | 22.62 | 3,920 | 22,516 |
| | C11 | 3.03 | 0.84 | 61.40 | 71.54 | 22.60 | 4,088 | 22,668 |
| **Window** | C12 | 3.20 | 0.78 | 64.35 | 74.50 | 23.13 | 3,320 | 21,014 |
| | C13 | 3.19 | 0.77 | 64.16 | 74.25 | 23.02 | 4,150 | 21,808 |
| | C14 | 3.17 | 0.77 | 63.91 | 73.97 | 22.95 | 4,980 | 22,595 |
| | C15 | 3.18 | 0.76 | 64.09 | 74.12 | 22.95 | 5,810 | 23,452 |
| **Ventilation** | C17 | 3.18 | 0.67 | 63.70 | 73.26 | 22.33 | 1,000 | 21,645 |
| | C18 | 3.18 | 0.64 | 63.62 | 73.04 | 22.16 | 1,000 | 21,619 |
| **Shading** | C20 | 3.38 | 0.82 | 67.98 | 78.69 | 24.42 | 1,250 | 22,126 |
| | C21 | 3.18 | 0.76 | 63.99 | 73.99 | 22.89 | 2,175 | 24,992 |
| **MVHR** | C22 | 1.57 | 0.77 | 32.73 | 39.65 | 13.80 | 4,000 | 21,914 |

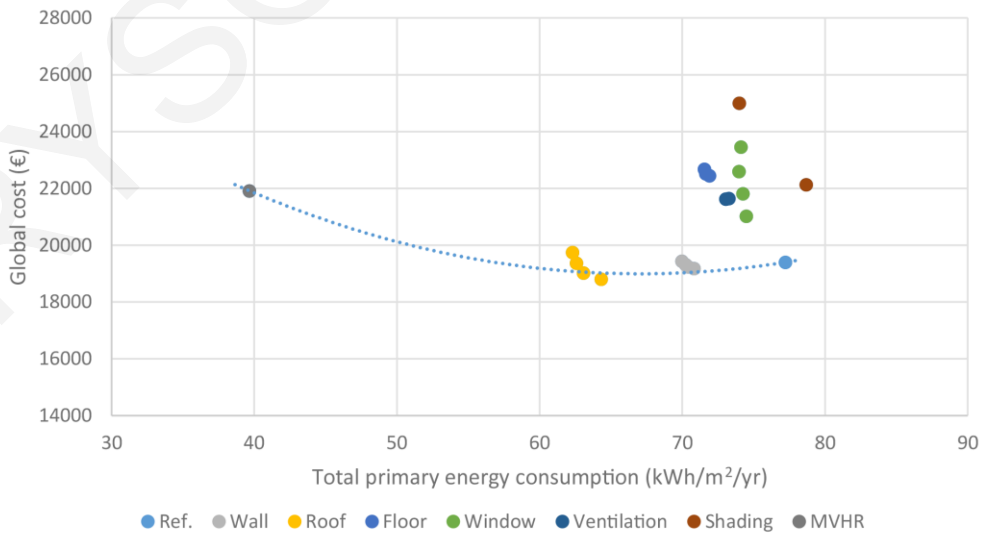



Figure 15.14. Cost optimality study-comparison for different individual retrofitting scenarios for a decrease of 0.5% in the rate of increase of the energy price.

In terms of the combinations, the lowest LCC compared to the reference building was provided by the scenario C29 where MVHR in combination with 10cm of insulation on the roof and 10cm of insulation on the wall were applied. The LCC of C29 is 14% higher compared to the reference building. The second lowest LCC was the scenario where the MVHR, 15 cm of insulation on the roof and 10cm of insulation on the wall were applied (i.e. C30). The LCC of C30 is higher by 15% compared to the reference building. Additional ventilation in the scenario C29, i.e. C31 provided an increase of the LCC by 27% and a decrease of primary energy consumption by 70%.

Table 15.17. Energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies for a decrease of 0.5% in the rate of increase of the energy price.

| **Strategy Combination** | **Scenarios** | **Annual Heating Load (MWh)** | **Annual Cooling Load (MWh)** | **Annual final cons. (kWh/m²/yr)** | **Annual primary energy (kWh/m²/yr)** | **Total $CO_2$ Emissi-ons $kgCO_2/m^2/y$** | **Invest-ment cost (€)** | **LCCA (€)** |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.18 | 1.17 | 65.17 | 77.24 | 25.49 | - | 19,399 |
| **Roof10cm +MVHR** | C23 | 1.18 | 0.51 | 24.49 | 29.38 | 9.99 | 7,444 | 22,054 |
| **Roof15cm +MVHR** | C24 | 1.17 | 0.50 | 24.12 | 28.93 | 9.82 | 7,864 | 23,495 |
| **Roof10cm +MVHR+ Vent** | C25 | 1.17 | 0.45 | 24.07 | 28.61 | 9.51 | 8,444 | 24,699 |
| **Roof15cm +MVHR+ Vent** | C26 | 1.15 | 0.44 | 23.71 | 28.17 | 9.35 | 8,864 | 25,053 |
| **Roof10cm +MVHR+ Wall8cm** | C27 | 0.92 | 0.51 | 19.47 | 23.86 | 8.53 | 8,965 | 23,100 |
| **Roof15cm +MVHR+ Wall8cm** | C28 | 0.90 | 0.50 | 19.02 | 23.31 | 8.33 | 9,385 | 23,437 |
| **Roof10cm +MVHR+ Wall10cm** | C29 | 0.91 | 0.51 | 19.23 | 23.60 | 8.46 | 9,063 | 22,067 |
| **Roof 15cm+MVHR+ Wall10cm** | C30 | 0.89 | 0.50 | 18.77 | 23.03 | 8.25 | 9,483 | 22,402 |
| **Roof10cm +MVHR+ Wall10cm+Vent** | C31 | 0.90 | 0.45 | 18.80 | 22.80 | 7.96 | 10,063 | 24,710 |
| **Roof15cm +MVHR+ Wall10cm+Vent** | C32 | 0.88 | 0.44 | 18.35 | 22.26 | 7.77 | 10,483 | 25,048 |
| **Roof10cm +MVHR+ Wall10cm+Window** | C33 | 0.93 | 0.45 | 19.42 | 23.52 | 8.18 | 14,043 | 25,689 |
| **Roof15cm +MVHR+ Wall10cm+Window** | C34 | 0.91 | 0.44 | 18.97 | 22.96 | 7.97 | 14,463 | 26,027 |
| **Roof10cm +MVHR+ Wall8cm+Wind.+Vent** | C35 | 0.93 | 0.39 | 19.26 | 23.05 | 7.80 | 14,945 | 28,283 |
| **Roof10cm +MVHR+ Wall10cm+Wind.+Vent** | C36 | 0.92 | 0.39 | 19.01 | 22.78 | 7.72 | 15,043 | 28,339 |
| **Roof15cm +MVHR+ Wall8cm+Wind.+Vent** | C37 | 0.91 | 0.38 | 18.82 | 22.52 | 7.61 | 15,365 | 28,624 |
| **Roof15cm +MVHR+ Wall10cm+Wind.+Vent** | C38 | 0.90 | 0.38 | 18.57 | 22.24 | 7.53 | 15,463 | 28,679 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Shading** | C39 | 0.93 | 0.41 | 19.33 | 23.22 | 7.92 | 16,218 | 31,323 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Floor5cm** | C40 | 0.72 | 0.48 | 15.39 | 19.21 | 7.14 | 17,851 | 29,617 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Roof 10cm+MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C41 | 0.71 | 0.38 | 14.89 | 18.17 | 6.43 | 21,026 | 37,104 |
| **Roof15cm +MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C42 | 0.68 | 0.36 | 14.38 | 17.56 | 6.22 | 21,446 | 37,252 |

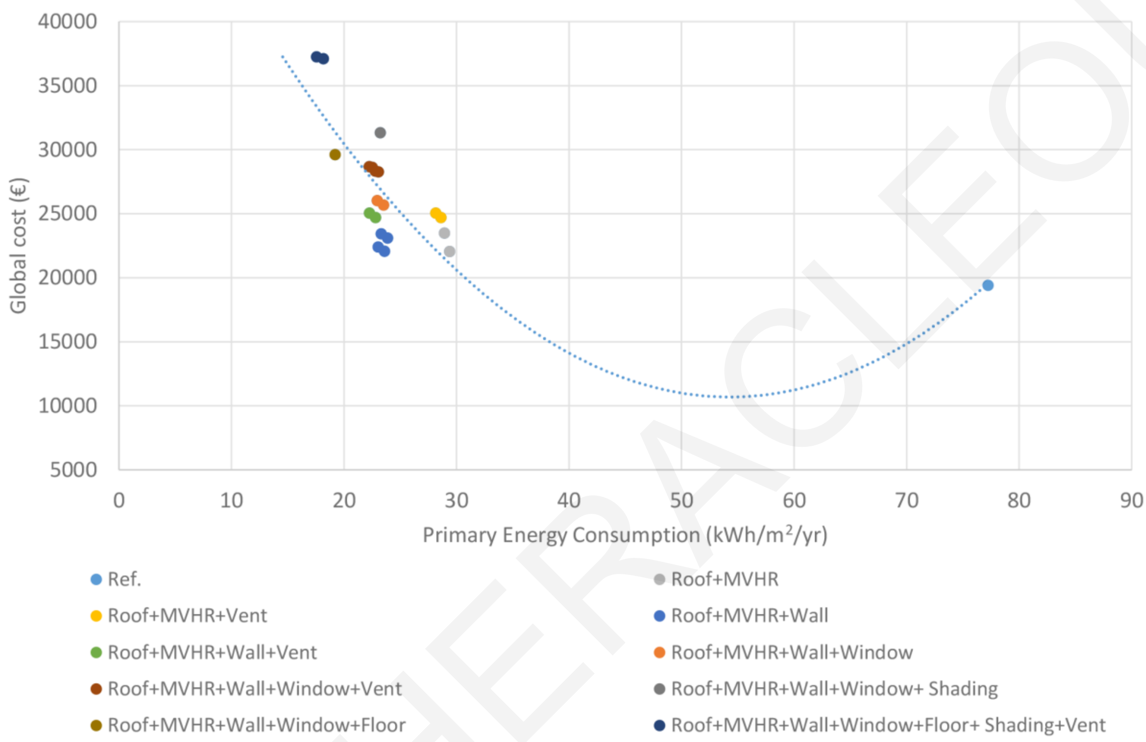



Figure 15.15. Cost optimality study-comparison for different combined retrofitting scenarios for a decrease of 0.5% in the rate of increase of the energy price.

*15.3.4.4. Extension of school curriculum during the afternoon*

In the context of an energy upgrade of school buildings, these buildings are now suitable for their further utilization.

The results of primary energy for the south oriented classroom of the first and ground floor in kWh/m$^2$/yr and in terms of percentage change compared to the base case scenario for the TMY are summarized in Table 15.18. The analysis was made for the academic year during the occupied hours 07:30-13:35 and 14:45-18:00.

As shown in the Table 15.18, all passive measures have higher impact on the reduction of primary energy consumption compared to the case where the building is occupied until midday (07:30-13:35).

Table 15.18. Predicted heating and cooling primary energy consumption and percentage of change compared to reference building using individual passive strategies and combinations thereof of south classrooms during hours of occupation (07:30-13:35 and 14:45-18:00) of the TMY.

**Occupied hours (07:30-13:35, 14:45-18:00)**

| TMY | First floor classroom | | | | | | Ground floor classroom | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Primary Energy Consumption (kWh/m²/year) | | | Percentage change (%) | | | Primary Energy Consumption (kWh/m²/year) | | | Percentage change (%) | | |
| | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total | Heating | Cooling | Total |
| Reference | 75.76 | 12.35 | 88.11 | - | - | - | 75.81 | 8.64 | 84.45 | - | - | - |
| C1 | 70.98 | 9.15 | 80.13 | -6.3 | -25.9 | -9.1 | 70.86 | 5.46 | 76.32 | -6.5 | -36.8 | -9.6 |
| C2 | 70.36 | 9.18 | 79.54 | -7.1 | -25.7 | -9.7 | 70.25 | 5.46 | 75.71 | -7.3 | -36.8 | -10.3 |
| C3 | 70.12 | 9.19 | 79.31 | -7.4 | -25.6 | -10.0 | 70.01 | 5.46 | 75.46 | -7.7 | -36.8 | -10.6 |
| C4 | 69.76 | 9.20 | 78.96 | -7.9 | -25.5 | -10.4 | 69.63 | 5.45 | 75.09 | -8.1 | -36.8 | -11.1 |
| C5 | 63.57 | 5.95 | 69.52 | -16.1 | -51.8 | -21.1 | 73.75 | 4.72 | 78.47 | -2.7 | -45.4 | -7.1 |
| C6 | 62.15 | 5.56 | 67.71 | -18.0 | -55.0 | -23.2 | 73.48 | 4.64 | 78.12 | -3.1 | -46.3 | -7.5 |
| C7 | 61.57 | 5.42 | 66.99 | -18.7 | -56.1 | -24.0 | 73.37 | 4.61 | 77.98 | -3.2 | -46.6 | -7.7 |
| C8 | 61.25 | 5.34 | 66.59 | -19.2 | -56.7 | -24.4 | 73.30 | 4.59 | 77.90 | -3.3 | -46.8 | -7.8 |
| C9 | 72.61 | 9.20 | 81.81 | -4.2 | -25.5 | -7.2 | 60.84 | 6.43 | 67.27 | -19.7 | -25.5 | -20.3 |
| C10 | 72.27 | 9.24 | 81.50 | -4.6 | -25.2 | -7.5 | 59.35 | 6.55 | 65.90 | -21.7 | -24.2 | -22.0 |
| C11 | 72.13 | 9.25 | 81.38 | -4.8 | -25.1 | -7.6 | 58.76 | 6.60 | 65.36 | -22.5 | -23.6 | -22.6 |
| C12 | 76.33 | 8.60 | 84.93 | 0.7 | -30.3 | -3.6 | 76.73 | 5.10 | 81.83 | 1.2 | -41.0 | -3.1 |
| C13 | 76.21 | 8.42 | 84.63 | 0.6 | -31.9 | -4.0 | 76.97 | 4.87 | 81.84 | 1.5 | -43.7 | -3.1 |
| C14 | 75.82 | 8.38 | 84.20 | 0.1 | -32.1 | -4.4 | 76.61 | 4.81 | 81.41 | 1.0 | -44.3 | -3.6 |
| C15 | 76.14 | 8.25 | 84.40 | 0.5 | -33.2 | -4.2 | 77.11 | 4.68 | 81.79 | 1.7 | -45.8 | -3.2 |
| C16 | 75.77 | 9.02 | 84.79 | 0.0 | -27.0 | -3.8 | 75.82 | 5.60 | 81.42 | 0.0 | -35.1 | -3.6 |
| C17 | 75.76 | 7.57 | 83.33 | 0.0 | -38.7 | -5.4 | 75.81 | 4.69 | 80.50 | 0.0 | -45.7 | -4.7 |
| C18 | 75.76 | 7.36 | 83.12 | 0.0 | -40.4 | -5.7 | 75.81 | 4.41 | 80.22 | 0.0 | -48.9 | -5.0 |
| C19 | 75.90 | 8.59 | 84.49 | 0.2 | -30.5 | -4.1 | 76.71 | 5.25 | 81.96 | 1.2 | -39.2 | -2.9 |
| C20 | 80.87 | 8.94 | 89.81 | 6.7 | -27.6 | 1.9 | 81.55 | 5.40 | 86.95 | 7.6 | -37.4 | 3.0 |
| C21 | 75.80 | 8.39 | 84.19 | 0.1 | -32.1 | -4.5 | 75.86 | 4.91 | 80.77 | 0.1 | -43.2 | -4.4 |
| C22 | 42.01 | 8.69 | 50.70 | -44.6 | -29.6 | -42.5 | 42.13 | 5.32 | 47.45 | -44.4 | -38.4 | -43.8 |
| C23 | 29.28 | 5.45 | 34.73 | -61.4 | -55.9 | -60.6 | 39.92 | 4.63 | 44.55 | -47.3 | -46.4 | -47.2 |
| C24 | 28.74 | 5.31 | 34.05 | -62.1 | -57.0 | -61.4 | 39.82 | 4.60 | 44.42 | -47.5 | -46.8 | -47.4 |
| C25 | 29.02 | 4.91 | 33.93 | -61.7 | -60.3 | -61.5 | 39.67 | 4.41 | 44.08 | -47.7 | -48.9 | -47.8 |
| C26 | 28.48 | 4.49 | 32.97 | -62.4 | -63.6 | -62.6 | 39.56 | 4.09 | 43.64 | -47.8 | -52.7 | -48.3 |
| C27 | 22.24 | 5.34 | 27.58 | -70.6 | -56.8 | -68.7 | 33.97 | 4.56 | 38.53 | -55.2 | -47.2 | -54.4 |
| C28 | 21.60 | 5.19 | 26.78 | -71.5 | -58.0 | -69.6 | 33.83 | 4.52 | 38.35 | -55.4 | -47.6 | -54.6 |
| C29 | 21.89 | 5.33 | 27.22 | -71.1 | -56.8 | -69.1 | 33.70 | 4.55 | 38.24 | -55.6 | -47.3 | -54.7 |
| C30 | 21.25 | 5.17 | 26.42 | -72.0 | -58.1 | -70.0 | 33.55 | 4.51 | 38.06 | -55.7 | -47.7 | -54.9 |
| C31 | 21.65 | 4.49 | 26.14 | -71.4 | -63.7 | -70.3 | 33.44 | 4.03 | 37.47 | -55.9 | -53.3 | -55.6 |
| C32 | 21.01 | 4.35 | 25.36 | -72.3 | -64.7 | -71.2 | 33.29 | 4.01 | 37.30 | -56.1 | -53.6 | -55.8 |
| C33 | 22.37 | 4.51 | 26.89 | -70.5 | -63.5 | -69.5 | 34.71 | 3.86 | 38.57 | -54.2 | -55.3 | -54.3 |
| C34 | 21.73 | 4.35 | 26.08 | -71.3 | -64.8 | -70.4 | 34.57 | 3.82 | 38.39 | -54.4 | -55.7 | -54.5 |
| C35 | 22.47 | 3.78 | 26.25 | -70.3 | -69.4 | -70.2 | 34.73 | 3.43 | 38.16 | -54.2 | -60.2 | -54.8 |
| C36 | 22.12 | 3.77 | 25.89 | -70.8 | -69.5 | -70.6 | 34.45 | 3.42 | 37.88 | -54.6 | -60.4 | -55.1 |
| C37 | 21.84 | 3.65 | 25.49 | -71.2 | -70.4 | -71.1 | 34.58 | 3.41 | 37.99 | -54.4 | -60.5 | -55.0 |
| C38 | 21.49 | 3.64 | 25.13 | -71.6 | -70.5 | -71.5 | 34.31 | 3.40 | 37.71 | -54.7 | -60.7 | -55.3 |
| C39 | 22.41 | 4.06 | 26.46 | -70.4 | -67.2 | -70.0 | 34.76 | 3.51 | 38.26 | -54.2 | -59.4 | -54.7 |
| C40 | 17.39 | 4.75 | 22.14 | -77.0 | -61.6 | -74.9 | 18.25 | 4.38 | 22.63 | -75.9 | -49.3 | -73.2 |
| C41 | 16.44 | 5.15 | 21.60 | -78.3 | -58.3 | -75.5 | 17.30 | 4.91 | 22.21 | -77.2 | -43.1 | -73.7 |
| C42 | 16.49 | 3.45 | 19.94 | -78.2 | -72.1 | -77.4 | 17.85 | 3.32 | 21.17 | -76.5 | -61.5 | -74.9 |

In order to demonstrate properly the impact of extension of school curriculum during the afternoon the energy performance and LCCA of different adaptation measures was calculated. Table 15.19 shows the energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies for the south oriented classroom in the first floor during hours of occupation (07:30-13:35 and 14:45-18:00).

As observed, the LCCA of retrofit scenarios has lower difference compared to the reference building, making them look even more effective when the building is occupied during the afternoon.

Table 15.19. Energy performance, $CO_2$ emissions and LCCA of individual retrofitting strategies for occupied hours 07:30-13:35 and 14:45-18:00.

| Compo-nent | Scena-rios | Annual Heating Load (MWh) | Annual Cooling Load (MWh) | Annual final cons. (kWh/m²/y) | Annual primary energy (kWh/m²/y) | Total $CO_2$ Emissions ($kgCO_2/m^2/y$) | Invest-ment cost (€) | LCCA (€) |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.55 | 1.54 | 73.45 | 88.11 | 29.96 | - | 22,063 |
| **Wall** | C1 | 3.32 | 1.14 | 67.92 | 80.13 | 26.15 | 1,391 | 21,524 |
| | C2 | 3.30 | 1.14 | 67.37 | 79.54 | 26.00 | 1,521 | 21,554 |
| | C3 | 3.28 | 1.14 | 67.15 | 79.31 | 25.95 | 1,734 | 21,613 |
| | C4 | 3.27 | 1.15 | 66.82 | 78.96 | 25.86 | 1,782 | 21,717 |
| **Roof** | C5 | 2.98 | 0.74 | 59.99 | 69.52 | 21.63 | 3,024 | 20,423 |
| | C6 | 2.91 | 0.69 | 58.56 | 67.71 | 20.95 | 3,444 | 20,535 |
| | C7 | 2.88 | 0.67 | 57.98 | 66.99 | 20.68 | 3,864 | 20,839 |
| | C8 | 2.87 | 0.67 | 57.66 | 66.59 | 20.54 | 4,284 | 21,196 |
| **Floor** | C9 | 3.40 | 1.15 | 69.41 | 81.81 | 26.62 | 3,808 | 24,896 |
| | C10 | 3.38 | 1.15 | 69.12 | 81.50 | 26.56 | 3,920 | 24,956 |
| | C11 | 3.38 | 1.15 | 69.00 | 81.38 | 26.53 | 4,088 | 25,103 |
| **Window** | C12 | 3.57 | 1.07 | 72.57 | 84.93 | 27.13 | 3,320 | 23,595 |
| | C13 | 3.57 | 1.05 | 72.40 | 84.63 | 26.96 | 4,150 | 24,382 |
| | C14 | 3.55 | 1.04 | 72.03 | 84.20 | 26.82 | 4,980 | 25,142 |
| | C15 | 3.57 | 1.03 | 72.28 | 84.40 | 26.81 | 5,810 | 26,010 |
| **Ventilation** | C17 | 3.55 | 0.94 | 71.68 | 83.33 | 26.17 | 1,000 | 24,159 |
| | C18 | 3.55 | 0.92 | 71.60 | 83.12 | 25.99 | 1,000 | 24,131 |
| **Shading** | C20 | 3.79 | 1.11 | 76.83 | 89.81 | 28.61 | 1,250 | 24,874 |
| | C21 | 3.55 | 1.04 | 72.02 | 84.19 | 26.82 | 2,175 | 27,527 |
| **MVHR** | C22 | 1.97 | 1.08 | 41.41 | 50.70 | 18.07 | 4,000 | 24,156 |

As shown in Table 15.19, all the cases of **wall retrofitting scenarios** provide lower LCC (ΔCg= -1.6-2.5%) for the 30 years of calculations compared to the reference building, making all the retrofitting options to be cost-effective. The higher the insulation, the higher the LCC, ranging from €21,524 to €21,717. The reduction of primary energy compared to the reference building is between 8-10 kWh/m²/yr.

As shown in Table 15.19, all the cases of **roof retrofitting scenarios** provide lower LCC (ΔCg= -4.0-7.4%) for the 30 years of calculations compared to the reference building and the cases of improved wall systems, making the roof retrofitting options to be cost-effective. Although the initial investment cost is higher than the improved wall system, the energy saving is correspondingly higher too. The higher the insulation, the higher the LCC ranging from €20,423 to €21,196. The reduction of primary energy consumption compared to the reference building is about 19-22 kWh/m²/yr.

As shown in Table 15.19 all the cases of **floor retrofitting scenarios** provide higher LCC (ΔCg= 13-13.9%) for the 30 years of calculations compared to the reference building. The higher the insulation, the higher the LCC ranging from €24,896 to €25,103. The reduction of primary energy consumption compared to the reference building is about 7 kWh/m$^2$/yr. The investment cost of this strategy is quite high and is considered as an advanced retrofitting option due to its difficulty to construct.

As shown in Table 15.19, all the cases of **window retrofitting** provide higher LCCA (ΔCg= 7-17.9%) for the 30 years of calculations compared to the reference building. The more advanced window system, the higher the LCCA ranging from €23,595 to €26,010. The reduction of primary energy consumption compared to the reference building is about 4 kWh/m$^2$/yr. Due to the fact that the investment cost is considered quite high compared to the impact on energy saving, windows alone do not seem to be such a cost-effective strategy for educational buildings.

As shown in Table 15.19 all the cases of **ventilation** provide higher LCCA for the 30 years of calculations compared to the reference building. The case of night ventilation alone provides slightly better LCC compared to the case of additional ventilation during daytime and nigh time due to the lower energy needs. Specifically, night ventilation alone, i.e. C18, has an LCC of €24,131 (ΔCg= 9.4%), while night ventilation associated with extra ventilation during daytime, i.e. C17, has an LLC of €24,159 (ΔCg= 9.5%). The reduction of primary energy consumption compared to the reference building is about 5 kWh/m$^2$/yr.

The case of **fixed shading** provides a higher LLC and a higher energy needs compared to the reference building and thus is not considered as a cost-effective strategy. The **movable shading** provides a higher LCC for the 30 years of calculations compared to the reference building, i.e. €27,527 (ΔCg= 24.7%). The reduction of primary energy consumption compared to the reference building is about 4 kWh/m$^2$/yr. Due to the fact that the south oriented classroom is shaded from the existing overhang used as corridor, the additional shading system alone does not seem to be a cost-effective strategy for south-facing classrooms. It has to be taken into consideration that for classrooms with other orientations, such as east or west the impact of shading systems on energy performance and LCC may be differentiated, as these classrooms do not incorporate the appropriate shading system.

The **MVHR** provides a higher LCC for the 30 years of calculations compared to the reference building, i.e. €24,156 (ΔCg= 9.5%). However, the reduction of primary energy consumption compared to the reference building is quite high at about 38 kWh/m$^2$/yr.

Figure 15.16 shows the LCCA of individual retrofit approaches according to different characteristics in correlation with the primary energy consumption.

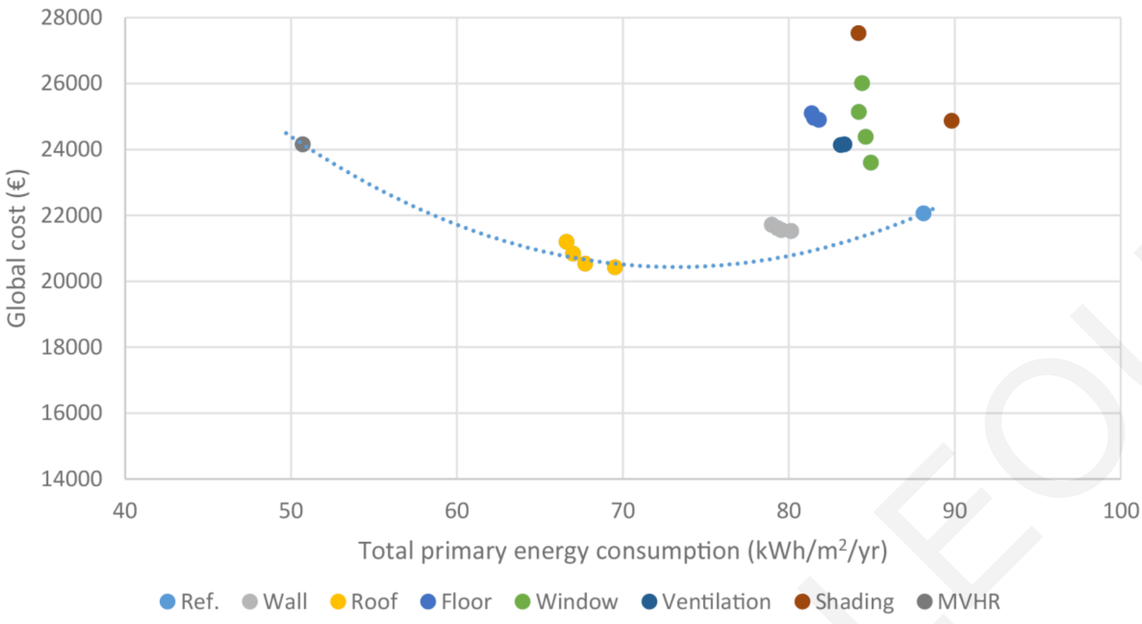



Figure 15.16. Cost optimality study-comparison for different individual retrofitting scenarios for occupied hours 07:30-13:35 and 14:45-18:00.

Table 15.20 tabulates the energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies for the south-oriented classroom on the first floor.

Table 15.20. Energy performance, $CO_2$ emissions and LCCA of combined retrofitting strategies for occupied hours 07:30-13:35 and 14:45-18:00.

| **Strategy Combination** | **Scenarios** | **Annual Heating Load (MWh)** | **Annual Cooling Load (MWh)** | **Annual final cons. (kWh/m²/yr)** | **Annual primary energy (kWh/m²/yr)** | **Total $CO_2$ Emissi-ons $kgCO_2/m^2/y$** | **Invest-ment cost (€)** | **LCCA (€)** |
|---|---|---|---|---|---|---|---|---|
| | Ref. | 3.55 | 1.54 | 73.45 | 88.11 | 29.96 | - | 22,063 |
| **Roof10cm +MVHR** | C23 | 1.37 | 0.68 | 28.63 | 34.73 | 12.12 | 7,444 | 23,261 |
| **Roof15cm +MVHR** | C24 | 1.35 | 0.66 | 28.09 | 34.05 | 11.86 | 7,864 | 24,662 |
| **Roof10cm +MVHR+ Vent** | C25 | 1.36 | 0.61 | 28.20 | 33.93 | 11.62 | 8,444 | 25,895 |
| **Roof15cm +MVHR+ Vent** | C26 | 1.33 | 0.56 | 27.56 | 32.97 | 11.14 | 8,864 | 26,170 |
| **Roof10cm +MVHR+ Wall8cm** | C27 | 1.04 | 0.66 | 22.20 | 27.58 | 10.16 | 8,965 | 23,968 |
| **Roof15cm +MVHR+ Wall8cm** | C28 | 1.01 | 0.65 | 21.55 | 26.78 | 9.86 | 9,385 | 24,260 |
| **Roof10cm +MVHR+ Wall10cm** | C29 | 1.03 | 0.66 | 21.88 | 27.22 | 10.06 | 9,063 | 22,917 |
| **Roof 15cm+MVHR+ Wall10cm** | C30 | 1.00 | 0.64 | 21.23 | 26.42 | 9.76 | 9,483 | 23,208 |
| **Roof10cm +MVHR+ Wall10cm+Vent** | C31 | 1.01 | 0.56 | 21.34 | 26.14 | 9.32 | 10,063 | 25,513 |
| **Roof15cm +MVHR+ Wall10cm+Vent** | C32 | 0.98 | 0.54 | 20.71 | 25.36 | 9.04 | 10,483 | 25,808 |
| **Roof10cm +MVHR+ Wall10cm+Window** | C33 | 1.05 | 0.56 | 22.01 | 26.89 | 9.53 | 14,043 | 26,508 |
| **Roof15cm +MVHR+ Wall10cm+Window** | C34 | 1.02 | 0.54 | 21.37 | 26.08 | 9.23 | 14,463 | 26,799 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Roof10cm +MVHR+ Wall8cm+Wind.+Vent** | C35 | 1.05 | 0.47 | 21.83 | 26.25 | 8.98 | 14,945 | 29,079 |
| **Roof10cm +MVHR+ Wall10cm+Wind.+Vent** | C36 | 1.04 | 0.47 | 21.51 | 25.89 | 8.88 | 15,043 | 29,117 |
| **Roof15cm +MVHR+ Wall8cm+Wind.+Vent** | C37 | 1.02 | 0.45 | 21.21 | 25.49 | 8.71 | 15,365 | 29,376 |
| **Roof15cm +MVHR+ Wall10cm+Wind.+Vent** | C38 | 1.01 | 0.45 | 20.88 | 25.13 | 8.61 | 15,463 | 29,413 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Shading** | C39 | 1.05 | 0.50 | 21.87 | 26.46 | 9.18 | 16,218 | 32,123 |
| **Roof10cm +MVHR+ Wall10cm+Window+ Floor5cm** | C40 | 0.81 | 0.59 | 17.57 | 22.14 | 8.39 | 17,851 | 30,566 |
| **Roof 10cm+MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C41 | 0.81 | 0.44 | 16.95 | 20.77 | 7.41 | 21,026 | 37,740 |
| **Roof15cm +MVHR+ Wall10cm+Window+ Floor5cm+Shading+ Vent** | C42 | 0.77 | 0.43 | 16.27 | 19.94 | 7.12 | 21,446 | 37,845 |

Scenarios C23-C24 combine the most effective cases in terms of energy saving, i.e. MVHR and roof insulation 10cm and 15cm thick. As observed, with an increase of 5% and 12% of the LCC compared to the reference building, the primary energy consumption is reduced by 53-54 kWh/m$^2$/year respectively. The LCC is €23,261 and €24,662 respectively.

Scenarios C25-C26 consider additional ventilation during daytime and nigh time in order to investigate its cost-effectiveness. As observed, with an increase of 17-19% of the LCC compared to the reference building, the primary energy consumption is marginally reduced (1%) compared to the previous scenarios, i.e. 54-55% reduction compared to the reference building. The LCC ranges from €25,895 to €26,170. The results show that a ventilation of 1000 l/s is not necessary during daytime and night time if the MVHR is installed.

Scenarios C27-C30 investigate the two best scenarios of wall and roof insulation in terms of the LCC, and indicate which case provides the best LCC when it is combined with the MVHR. The best-case scenario is the one with the 10cm insulation on the roof and the 10cm insulation on the wall, in combination with the MVHR (C29), giving the lowest LCC at €22,917. The results show that primary energy consumption is reduced by 61 kWh/m$^2$/year for only a 4% increase of LCC compared to the reference building. Here it is worth mentioning that although the investment cost is higher compared to the aforementioned cases, the reduction of primary energy consumption offsets this difference. Moreover, as the numbers indicate, a 10cm wall insulation works better in terms of lower LCC and energy saving compared to the wall with 8cm insulation. Additionally, the difference between 10cm and 15cm of insulation on the roof has a minor difference regarding the LCC and therefore the best in terms of performance (i.e. 15cm insulation) can be used. However, for each combination the analysis presents data for both two cases in order to have an overview of the performance for both cases.

Scenarios C31-C32 again include additional ventilation to the one in the aforementioned C29-C30 scenarios in order to identify whether it has a higher impact on a more insulated building envelope. Again, the energy performance of these scenarios is only 1% lower compared to the C29-C30 scenarios. The LCC is about 16-17% higher than the reference building ranging from €25,513 to €25,808 with a total reduction of primary energy of about 62-63 kWh/m$^2$/year.

Scenarios C33-C34 include improved windows to the ones in scenarios C29-C30 in order to achieve an optimally insulated building envelope, avoiding condensation. It is worth mentioning that in order to be compatible with the Law and the minimum requirements set therein, the double low-e with insulated frame window system was selected for analysis. It has to be noted that with an increase of 20-21% of the LCC (€26,508 - €26,799) compared to the reference building, a reduction of primary energy consumptions is minor compared to scenarios C29-C30 that do not include window replacement, i.e. only 0.3 kWh/m$^2$/year compared to C29-C30. Again, the combinations showed that windows are not a cost-effective solution.

Scenarios C35-C38 examine the addition of ventilation to the aforementioned cases C33-C34 but also examine the performance of different insulation thicknesses on the wall. The results showed an increase of the LCC by about 32-33% compared to the reference building, i.e. €29,079 - €29,413with a reduction of primary energy consumption by 62-63 kWh/m$^2$/year.

The C39 scenario examines the impact of adding shading devices to the aforementioned C33 scenario, both in terms of energy performance and LCC. The results showed an increase of the LCC by about 46% compared to the reference building, i.e. €32,123 with a reduction of primary energy consumption by 62kWh/m$^2$/year. Again, the combinations show that a shading system in the south-oriented classroom is not necessary nor cost-effective.

The C40 scenario investigates the addition of insulation on the ground floor to the aforementioned scenario C33. The results show an increase of the LCC by about 39% compared to the reference building, i.e. €30,566 with a reduction of primary energy consumption by 66 kWh/m$^2$/year.

Scenarios C41-C42 combine all the examined types of retrofit with different roof insulation in order to achieve the maximum energy performance and to identify the impact on the LCC. The results showed an increase of the LCC by about 71-72% compared to the reference building, i.e. €37,740 and €37,845 with a reduction of primary energy consumption by 67-68 kWh/m$^2$/year. This shows that the advance retrofitting scenario is not a cost-effective solution for the improvement of energy performance of educational buildings.

Figure 15.8 shows the LCCA of combined retrofit approaches according to different characteristics. The curve represents a theoretical set of optimal solutions by considering the reference building as a starting point. As shown, the application of roof insulation in combination with the addition of MVHR and wall insulation has the lowest cost with a significant reduction in energy consumption compared to the reference building.

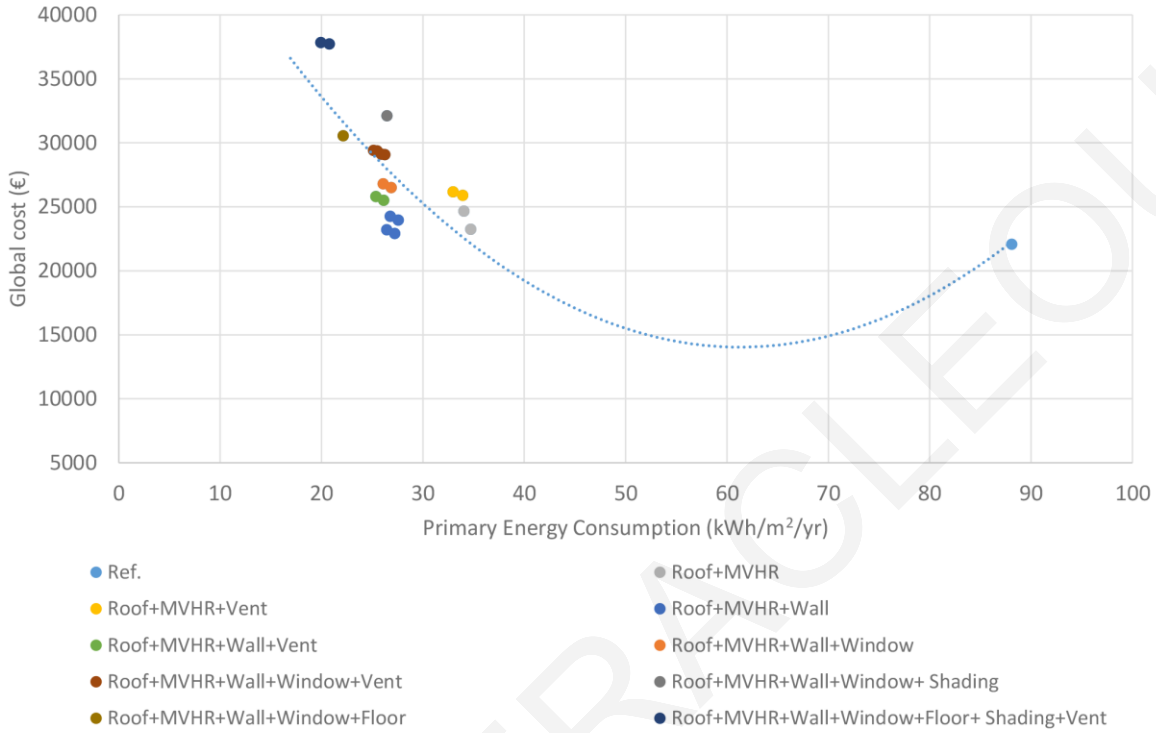



Figure 15.17. Cost optimality study-comparison for different combined retrofitting scenarios for occupied hours 07:30-13:35 and 14:45-18:00.

This thesis also examined different energy prices and discount rate were examined for the case where educational buildings are used until the afternoon. The sensitivity analysis has shown that the higher discount rate of 3% throughout the entire calculation period led to a decrease of the global cost, both regarding the reference building as well as the proposed retrofitting options. Specifically, the global cost of the reference building was € 15,425 while the global cost of the most cost-effective strategy C29 was €18,910. A higher development of the energy price leads to reduction of LCC of the most effective combination C29 at the same level as the reference building. Specifically, the LCC of the reference building is €23,246, while the LCC of C29 is €23,277. A lower development of energy price reduced the LCC of the reference building as well as of the retrofit interventions. The LCC of the reference building is €20,986. In terms of the combinations, the lowest LCC compared to the reference building was provided again by case C29 where MVHR in combination with 10cm of insulation on the roof and 10cm of insulation on the wall were applied with an increase of LCC at 8%.

## 15.4. Synopsis and Discussion

### *15.4.1. Synopsis regarding on-site experimental procedure for proper operation of windows*

The study includes a comparative analysis of indoor conditions, via the evaluation of air and operative temperatures of four south-oriented classrooms that adopted a range of diverse strategies for ventilation and window opening patterns during the heating and cooling periods. The results highlight the effectiveness of an appropriate manual airing pattern, which aims to maximize the hours within the comfort zone. Moreover, results demonstrate the influence of ventilation on indoor conditions during the winter period.

The study provides evidence that night ventilation during the warm period is an effective strategy to reduce the cooling degree-hours as this can decrease peak air temperature by up to 5.2°C below the peak outdoor air temperature (Figure 15.1). This finding aligns with a comparative research carried out in an Israeli apartment building by Shaviv et al. [489] who maintain that applying night ventilation can decrease the peak temperature of the air by up to 6°C. During the application of night ventilation, the nocturnal indoor air temperatures closely follow the outdoor environment and the following day peak indoor air temperatures are reduced. Additional studies carried out in Cyprus exhibit similar results [196], as well as similar studies performed in other regions [73], [202], which recommend night ventilation in regions with great climatic variations between night and day. It should be noted that south-orientated classrooms undermine the cross ventilation strategy, as the prevailing nocturnal winds have west direction. The impact of cross-ventilation during the night is greater on west/east oriented classrooms (Figure 15.1). Moreover, it is worth mentioning that the behaviour of classrooms with cross-ventilation strategies implemented only during the night is similar to the behaviour of classrooms that apply cross-ventilation for both day and night in terms of thermal and energy performance; therefore, it is suggested to apply ventilation during the day and night in order to increase air velocity within the occupied zone as well as to ensure high levels of indoor air quality. Based on the European Standard EN 15271:2007 [87], increasing the rate of motion of the air can be a way to make up for higher temperatures in the air. Ventilation and glazing are also necessary to remove heat gains produced by occupants during the teaching hours. In a similar vein, a study on the indoor thermal environments in a naturally ventilated residential building in Singapore by Liping and Hien [80] indicated that the most efficient strategy is night ventilation over daytime ventilation, while in case of buildings with low thermal inertia, full-day ventilation is more effective. The calculation of temperature difference ratio (TDR) and cooling degree-hours (CDH) for different ventilation strategies confirms that cross-ventilation during the night offers the best possible indoor thermal comfort conditions.

Moreover, the findings of this study also highlight the significance of occupants' behaviour in the performance of educational buildings. Window-opening patterns relate both to the indoor and outdoor air temperature and more extensive results on occupant behaviour are available in **Chapter 16.2.1** [490]. These agree with the results in the study of the Rijal et al. [167] who state that window-opening behaviour can be predicted from the temperature. In addition, the thesis shows that we need additional detailed and succinct research and understanding of the occupants' role during the winter period in order to ensure appropriate indoor thermal comfort and air quality levels as well as to define the modified thermal sensation votes using the Griffith's method [135].

### *15.4.2. Synopsis regarding the impact of ventilation on overheating risk*

The current study addresses the impacts of climate change on the thermal performance of educational buildings in Cyprus and assesses the overheating risk for the TMY, 2050, and 2090 using different ventilation patterns in the dynamic software simulation IES-VE.

The projected rise in both average and extreme temperatures in the future will make buildings more uncomfortable to live in and potentially dangerous for the occupants' health because of the high internal temperatures in poorly ventilated environments. The present study shows that typical classrooms are predicted to suffer from overheating more than half of the occupied time in 2050 while in 2090, more than 70% of the time in all orientations. A summary of the research findings, i.e., the ventilation strategies criteria for the TMY and future climatic predictions, is presented in a comparative manner in Figure 15.18. Moreover, Figure 15.19 shows the percentage reduction of the TM52 overheating criteria values, caused by different ventilation strategies under study.

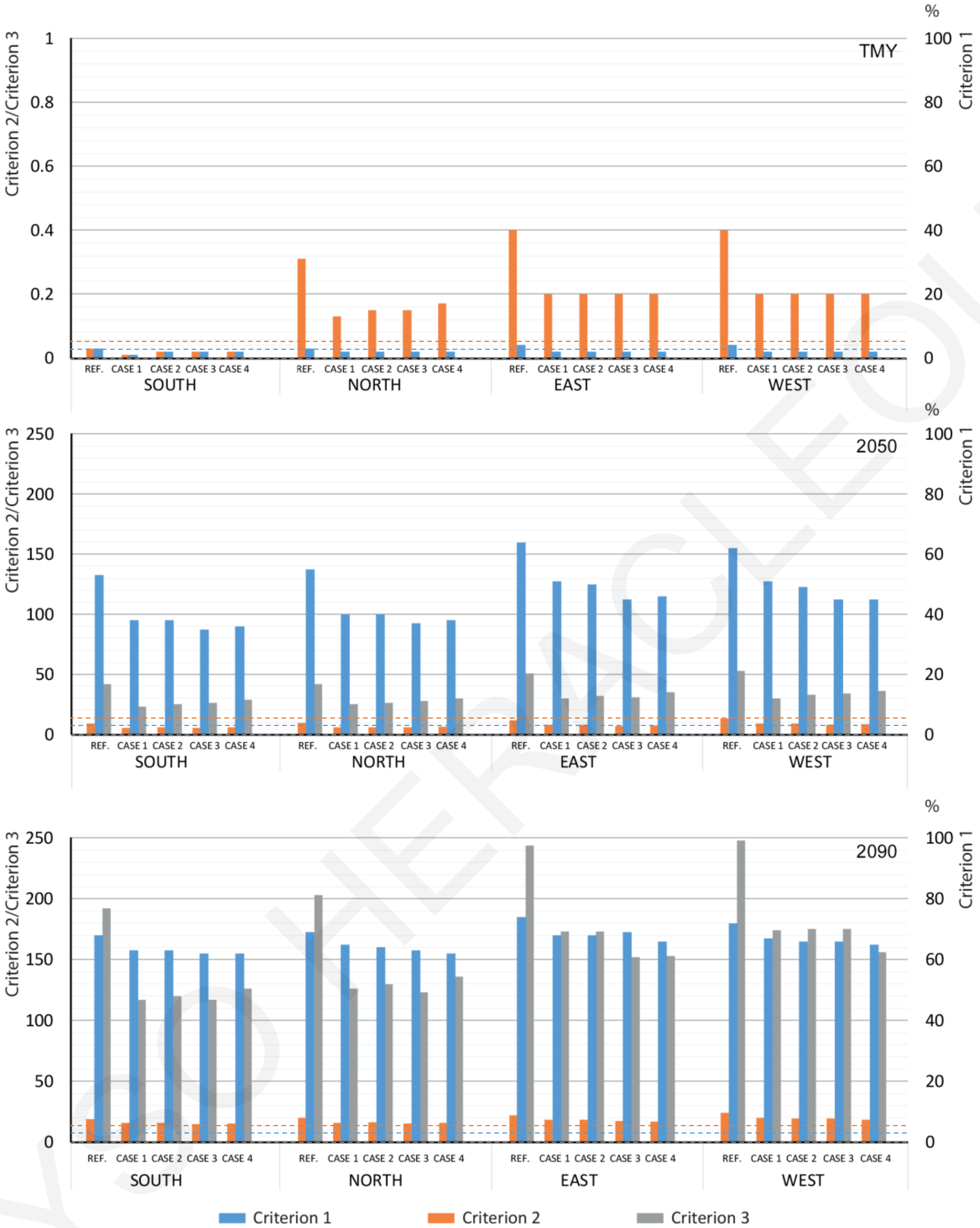



Figure 15.18 Summarized results of ventilation strategies for the TMY and climatic predictions, i.e. for 2050 and 2090. It is noted that the results for criteria 2 and 3 for 2050 and 2090 are presented in a different scale in the y axis due to much higher values compared to TMY. Dot lines indicates the threshold of each criterion and have the same colour with the criterion.


Figure 15.19. Percentage reduction of the TM52 overheating criteria values, caused by different ventilation strategies under study.

Climatic change is expected to also result in productivity reduction, in a need to retrofit mechanical ventilation or cooling systems, as well as in depreciation of property values. Climatic variability will also affect the performance of building technical services because of the inconsistent power outages and quality, the prolonged cold and rainy seasons, the flooding and intense heat wave as well as winter storms. Buildings designed according to existing standards may become increasingly costly to operate and maintain in the future [491].

The study assesses the potential of ventilative cooling as a mitigation strategy. Proper and adequate ventilation meliorates indoor air quality (IAQ) by diluting the concentration of pollutants that are present indoors, introducing fresh air from outdoors and removing polluted indoor air. In addition, the learning ability of students is found to be associated with fresh air circulation in the classrooms [492]. Apart of the positive impact on the IAQ, natural ventilation is considered as effective strategy for reducing energy consumption. Results show that night ventilation in the current climatic conditions is able to fully eliminate the overheating in all orientations. This is in line with the study performed by Michael et al. [196], which indicates that the night ventilation strategy has a positive impact on the cooling effect of the indoor spaces of vernacular buildings during the hot summer period. However, ventilative cooling will not be able to fully eliminate the increasing risk of overheating in the future. Specifically, in the best case, it can reduce overheating by 28-35% in the 2050s and by 9-11% in the 2090s depending on the orientation. In a future characterized by significantly warmer summer temperatures and an increase in extreme climatic events, additional strategies should be taken into consideration. In this context, active cooling may become necessary to maintain thermal comfort and even to safeguard life. This is line with other research studies studies [350], [351], [357]–[359], indicating a series of control cooling strategies such as airing, solar shading and mechanical cooling with stand-alone room air conditioners.

Based on the same methodology, in a future implementation study, the impact of climate change can be analysed in winter and midterm weather conditions. Although these periods are not commonly considered to be at overheating risk, it should be noted that according to the adaptive response method (EN 15251), occupants are much more likely to be sensitive to high temperatures during colder periods. The above indicates that overheating issues can also occur during the midterm and winter period and thus, form a field for further research. Moreover, the evaluation of the thermal performance of buildings in future climatic conditions beyond the years of 2050 and 2090 can also be a field of further investigation once the climatic data is available for use.

The impact of climate change is expected to be further aggravated for typical classrooms in the top floors of buildings, and in city centres, as a result of the urban heat island effect. Future research should consider these factors in analysing the effect of climate change. The densification of cities, in correlation with the increase in living standards, will intensify the overheating scenario.

The current research focuses on the positive impact of natural ventilation as a mitigation passive strategy that improves indoor air quality and health while, in an indirect manner, it influences the learning capacity and performance of students. The implications of energy use and consequently of the economic saving resulting from the implementation of the natural ventilation strategy form a field for further investigation in future research studies. As occupant behaviour is a significant factor affecting the thermal performance of the building, it also requires further investigation. Alternative strategies to deal with overheating in buildings need to be promoted; i.e., strategies that do not fully rely on active systems which are dependent on energy derived from fossil fuels.

Using the EN 15251 and CIBSE TM52 criteria, the present study aimed to predict the vulnerability of buildings to climate change and possibly, to suggest ways by which they can be adapted to assess the long-term sustainability of new and existing educational buildings.

### *15.4.3. Synopsis regarding adaptation measures through software simulation*

The key aspect of the study includes an assessment and analysis of the impact of climate change on thermal comfort and the energy performance of educational buildings, and bring to the fore how essential it is to timely plan retrofitting actions to mitigate the predicted effect. The case study building has been modelled and calibrated using dynamic simulation software (IES-VE), in order to determine the potential impact of climate change (2050, 2090) under the A1B scenario.

For the improvement of thermal comfort and energy performance of educational buildings in Cyprus both in the current and future climatic conditions, adaptation measures were proposed. It must be noted that the application of proposed improvements should be made after thorough consideration and examination of the building, as results may vary depending on the type of building, typology, construction materials, operation etc.

For example, educational buildings which operate until noon have much higher heating needs than for cooling. Fixed additional shading devices, as a way to reduce overheating hours in the summer, will have a negative impact during the heating period due to blocking solar gains. Taking into consideration that school buildings are closed during summer time to avoid overheating, additional fixed shading is not deemed as an appropriate strategy. Movable shading could provide better results in terms of comfort and energy, eliminating the negative impact during the winter period. Specifically, movable shading can reduce cooling needs by 30% in the TMY and by about 20% in the future. This is in line with the study undertaken by Andric et al. [367], which proposes that the performance of shading systems varies depending on the climate.

Thermal insulation is generally beneficial both during the current and future climatic scenarios. The study highlights the importance of roof insulation for the summer period (66-75% in TMY) but also during the winter period (4-5% in TMY). Although, the addition of wall and floor insulation results in an increase of cooling degree hours (13-16%), due to the reduced thermal bridges through the walls and floor, it is considered an important measure for improving building performance during the winter period, when the need for heating is predominant. The beneficial aspect of windows is negligible for cooling and increase heating needs, due to a reduction of solar gains. Radhi [362] also mentions that lowering the g-value of glass might have adverse results in cooler, higher latitudes, where solar gains are beneficial. However, improved windows were considered in the combination measures, in order to avoid temperature surface variations and condensation problems. Also, the comparison between scenarios C23 and C24, whereby the building envelope is insulated, shows a variation in the U- value of the window, with C24 being the more efficient one, indicating that the lower the U-value, the better the performance. The overall insulation of the building envelope (C26) leads to an overall reduction of degree hours by 26% in the TMY, 30% in 2050 and 35% in 2090. This is in agreement with the results in the study of Invidiata and Ghisi, 2016 [363] which reaches the conclusion that insulation reduces the total energy demand by 27% in hot and humid climates.

The study reveals that natural ventilation during day and night could reduce cooling degree hours by 62%. The results are in line with Van Hooff et al. [365], who found that natural ventilation reduces the cooling demand in a residential building by 60%. Its combination with roof insulation could almost prevent the need for active cooling entirely during the TMY with about 97% reduction while, in the future, the effectiveness decreases due to hotter nights to 91% in 2050 and 85% in 2090.

The combination of all passive measures (C31) shows a reduction of heating degree hours by about 24% and a total reduction of cooling loads (100%) leading to a reduction of total degree hours by 27% in TMY, while the effectiveness of combinations is higher in the future. Specifically, passive measures reduce the total degree hours by 32% and 39% in 2050 and 2090 respectively. The addition of heat recovery ventilation to the previous scenario (i.e., C32), to improve both thermal comfort and air quality, reduces the total degree hours by 51% in the TMY (i.e., additional 25% reduction to C31 scenario), and by 60% and 66.4% during 2050 and 2090. In addition, it is interesting to mention that during current climatic conditions and in 2050, these combinations prevent the need for active cooling, while, in 2090 the use of active systems to maintain thermal comfort may be considered. This is in line with the study conducted by Osman and Sevinc [493] which stated that strategies must shift to more active-cooling by 2070 when natural ventilation will no longer be a beneficial design strategy for all seasons.

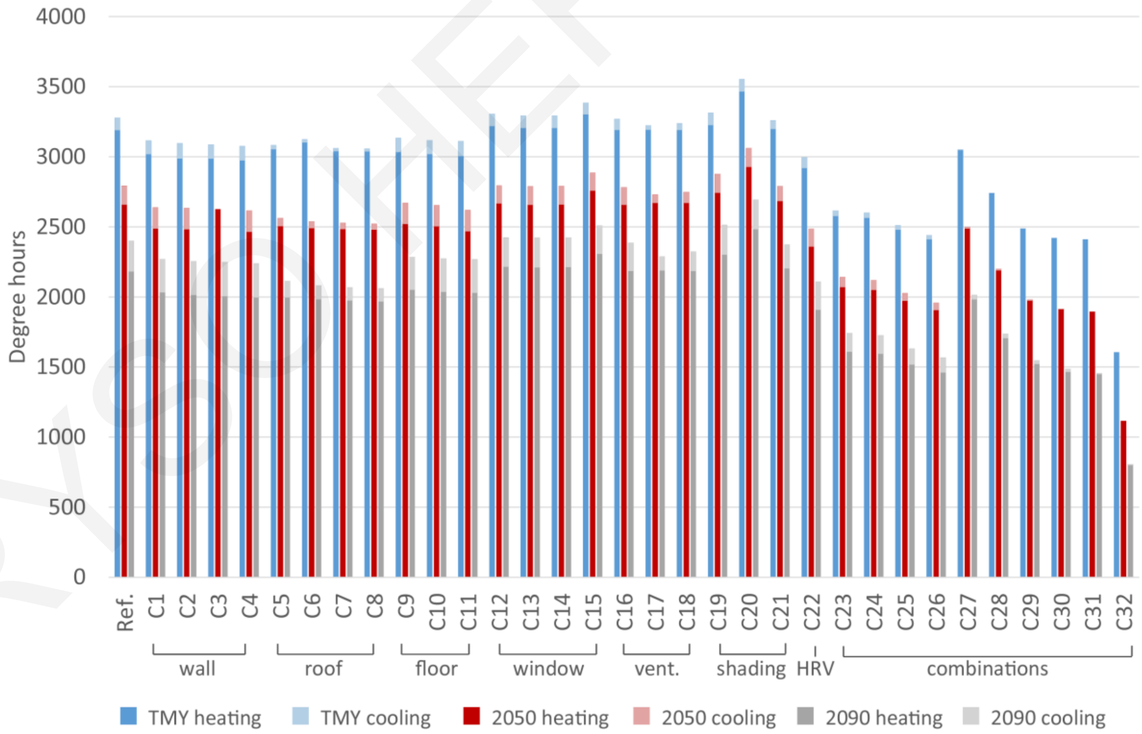



Figure 15.20. Predicted heating, cooling degree hours using individual passive strategies and combinations thereof, in a south classroom on the first floor during hours of occupation (07:30-13:35) for the TMY, 2050 and 2090 using the 80% acceptability limit.

*15.4.4. Synopsis regarding energy performance and cost-effectiveness of adaptation measures and sensitivity analysis*

The key aspect of this study is to include an assessment and analysis of the energy performance and cost-effectiveness of adaptation measures in educational buildings, and bring to the fore how essential it is to plan timely retrofitting actions to mitigate the predicted effect according to the selected analysis criteria of suitable energy measures. The case study building has been modelled and calibrated using dynamic simulation software (IES-VE), therein applying technical systems in order to determine the energy performance of the educational building under the current climatic conditions.

For the improvement of thermal comfort and energy performance of educational buildings in Cyprus, adaptation measures used for the previous evaluation of the building under the free-running conditions were used. However, the combinations were based on the best performance of individual scenarios in terms of the LCCA and on whether they meet the Minimum Energy Performance Requirement as dictated by the Law. The evaluation was based on two steps of analysis, first the energy-demand modelling and retrofit option ranking, and the second, the LCCA –based cost effectiveness estimations.

The results showed that providing a heat recovery ventilation unit has the highest energy-saving ranking at about 49%, followed by the installation of roof insulation, reducing the primary energy consumption by about 18%. The third energy saving measure is the insulation of the walls, minimizing the total primary energy consumption by about 9%, while night ventilation lowers the total primary energy consumption by about 5%. Windows provide a reduction of primary energy consumption by about 3-4%. Shading devices have a small effect on the total energy saving measured at 2-3%, as classrooms are located south and the overhang created by the external corridor is considered adequate. The results are in line with the study performed by Wang and Holmberg, [425], who found that the highest energy saving ranking was the one proposing the addition of MVHR, roof and wall insulation.

In the first investigation, by considering a discount rate of 0% (in real time) that has an increase of up to 1.08% over the 30 years of calculation, the reference building (south-oriented classroom on the first floor) has the highest primary energy demand (77.2 $kWh/m^2/yr$) with a global cost of about €20,347.

The results of the LCCA have shown that mechanical ventilation with heat recovery, and 10cm roof insulation as well as 10cm wall insulation are the most suitable energy efficient measures according to the selected analysis criteria. Specifically, this scenario (C29) reduced the primary energy demand by 69% with a small increase of global cost by 10%, i.e. € 22,352. The alternative of installation of 15cm of insulation on the roof instead of 10cm is also considered as a cost-effective strategy as the difference in the LCC is minor (only 1% compared to the aforementioned scenario, i.e. € 22,681) minimizing the energy demand by 70%.

The sensitivity analysis has shown that the higher discount rate of 3% throughout the entire calculation period led to a decrease of the global cost, regarding both the reference building as well as the proposed retrofitting options increasing the risk of cost-effectiveness of adaptation measures. Specifically, the global cost of the reference building was €14,246 while the global cost of the most cost-effective strategy C29 was €18,522.

Variation in the energy price affects the results of the LCC. A higher development of the energy price supports the selection of the solutions characterized by the lower energy demands. The increase of the energy price leads to a higher LCC of the reference building and a reduced LCC of the retrofitting interventions as the major incidence on the global cost is given by the overall energy costs. The LCC of C29 is 6% higher than the reference building providing however, a 69% reduction in the primary energy consumption compared to the reference building. The second lowest LCC was the scenario where MVHR, 15cm of insulation on the roof and 10cm of insulation on the wall were applied (i.e. C30). The LCC of C30 was higher by only 7% compared to the reference building. The sensitivity analysis shows that the higher the increase on energy price the lower the difference in the LCC compared to the reference building.

A lower development of energy price reduced the LCC of the reference building as well as of the retrofit interventions. As the rate of increase of energy price is decreased, the interventions have lower value as the overall energy cost is decreased. The LCC of the reference building is €19,399. In terms of the combinations, the lowest LCC compared to the reference building was provided again by case C29 where MVHR in combination with 10cm of insulation on the roof and 10cm of insulation on the wall were applied, with an increase of LCC at 14%.

The sensitivity analysis on the school curriculum has shown that adaptation measures are considered even more effective when the curriculum is extended during the afternoon as the difference in the LCCA compared to the reference building is minimized. This is an important decision-making element that emphasizes the need for energy upgrades so that school buildings are suitable throughout the day. Specifically, this scenario (C29) reduces the primary energy demand by 69% with a small increase of global cost by 4%, i.e. € 22,063 compared to the €21,917 of the reference building. The alternative of installation of 15cm of insulation on the roof instead of 10cm is also considered as cost effective strategy as the difference in the LCC is minor (only 1% compared to the aforementioned scenario, i.e. €23,208) minimizing the energy request by 70%. Considering a further increase of energy price in the future, make the LCC of C29 under an extended curriculum almost the same with the reference building. The presented results underline that the selection of input parameters is highly influential and the cost optimal methodology may be a powerful tool for sustainability, but it requires sensitivity and expertise.

# Chapter 16. Assessment of indoor air quality of educational buildings and the impact of natural ventilation under current climatic conditions

## 16.1. Introduction

This chapter is organized into three main subdivisions to present the analysis of evaluation of air quality of existing educational buildings under current climatic conditions for the warm, intermediate and cool seasons. The first section of this chapter describes the results from the experimental procedure using field measurements of environmental variables for each season; the second reports the results of monitoring of occupant behaviour regarding manual control of windows, and the third section describes the results of the qualitative approach through questionnaires under different seasonal climatic conditions. Finally, a synopsis and discussion and a chapter summary are provided.

## 16.2. Results of experimental period for natural ventilation through field measurements

### *16.2.1. Monitoring of occupant behaviour regarding the manual control of windows through filed observation*

The behaviour of occupants vis-à-vis window manual control in educational buildings was monitored for three days of the week in the four classrooms in all seasons. The monitoring intended to trace the relation between the daily activity of the occupants and window control patterns so as to quantify the impact that environmental variables have on the window-opening and closing behaviour of occupants. Moreover, the monitoring assessed the IAQ of classrooms under the in-use scenario and the effectiveness of different window patterns. Window opening as a ventilation strategy does not only benefit the indoor environment but also improves thermal comfort.

Table 16.1 shows the external conditions only during occupied hours, i.e., 07:30-13:35 and presents a compilation of the indoor recorded values of the same period during the monitoring of occupant behaviour.

Table 16.1. Synthesis table of all the recorded values carried out for the investigation of the impact of natural ventilation on both thermal comfort and air quality in educational buildings.

| | | Minimum Values | | | | Maximum Values | | | | Average Values | | | | Standard Deviation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Experiment Type - Period | Parameter | R1 | R2 | R3 | R4 | R1 | R2 | R3 | R4 | R1 | R2 | R3 | R4 | R1 | R2 | R3 | R4 | Ref. Values |
| **Occupant behaviour manual window control** 1st monitoring period (14.2.2018 – 16.2.2018) | Room temperature (°C) | 17.9 | 17.2 | 17.4 | 16.8 | 23.2 | 21.9 | 23.1 | 21.1 | 21.1 | 19.7 | 20.7 | 19 | 0.9 | 0.8 | 0.9 | 0.7 | 19.4-25.4 |
| | Relative Humidity (%) | 37.5 | 40.1 | 45.5 | 46.9 | 61.4 | 63.4 | 67.0 | 72.5 | 51.8 | 52.4 | 56.7 | 61.5 | 2.1 | 2.9 | 2.7 | 3 | 30-70 |
| | $CO_2$ concentration (ppm) | 433 | 425 | 426 | 410 | 2585 | 1897 | 2978 | 2703 | 1163 | 947 | 1180 | 1006 | 417 | 355 | 399 | 408 | ≤ 1500 |
| | External temp. (°C) | 9.7 | | | | 18.4 | | | | 15.6 | | | | 2.2 | | | | |
| | External RH (%) | 45 | | | | 84 | | | | 63.9 | | | | 7.3 | | | | |
| **Occupant behaviour manual window control** 2nd monitoring period (7.3.2018 – 9.3.2018) | Room temperature (°C) | 21 | 20 | 20.2 | 18.9 | 23.9 | 23.3 | 23.6 | 21.9 | 22.3 | 21.7 | 21.9 | 20.2 | 0.6 | 0.6 | 0.7 | 0.6 | 20.2-26.2 |
| | Relative Humidity (%) | 37 | 40 | 44.1 | 40.8 | 63.3 | 67.9 | 69.7 | 72.7 | 53.3 | 55.7 | 58.1 | 59.6 | 3.3 | 3.4 | 2 | 4.6 | 30-70 |
| | $CO_2$ concentration (ppm) | 391 | 389 | 406 | 406 | 1836 | 1745 | 2090 | 1598 | 806 | 904 | 867 | 702 | 375 | 371 | 276 | 241 | ≤ 1500 |
| | External temp. (°C) | 13.4 | | | | 24.2 | | | | 19 | | | | 2.9 | | | | |
| | External RH (%) | 39 | | | | 95 | | | | 61.7 | | | | 13.3 | | | | |
| **Occupant behaviour manual window control** 3nd monitoring period (19.5.2018 – 22.5.2018) | Room temperature (°C) | 21.6 | 23.2 | 23.0 | 22.6 | 31.1 | 31.5 | 31.7 | 31.8 | 28.5 | 28.4 | 29.0 | 28.6 | 0.8 | 0.7 | 0.7 | 1.0 | 24.3.2-30.3 |
| | Relative Humidity (%) | 22.4 | 19.3 | 23.4 | 20.5 | 55.2 | 51.2 | 54.2 | 55.5 | 33.2 | 33.8 | 38.3 | 35.5 | 3.15 | 4.8 | 4.2 | 5.6 | 30-70 |
| | $CO_2$ concentration (ppm) | 419 | 408 | 439 | 392 | 1370 | 1352 | 1822 | 1473 | 618 | 685 | 718 | 708.4 | 193 | 228 | 230 | 241 | ≤ 1500 |
| | External temp. (°C) | 20.7 | | | | 36.6 | | | | 30.3 | | | | 3.8 | | | | |
| | External RH (%) | 14 | | | | 54 | | | | 28.5 | | | | 7.8 | | | | |

*16.2.1.1. Recording periods from the 14th of February to the 16th of February, 2018 and from the 7th to the 9th of March, Winter period.*

Results showed that $CO_2$ concentration indoors and the temperature outdoors form the two key variables in determining how probable it is to open or close windows respectively. Peak values of $CO_2$ during the monitoring reached approximately 3000ppm indicating that students cannot always identify poor air quality and that thermal comfort is probably the most important parameter in indoor environmental quality evaluation. Studying the mean values of $CO_2$ concentration both in the first and second experimental monitoring periods (Table 16.1), it becomes evident that mean values of $CO_2$ concentration during the second monitoring period are lower in all classrooms. This is attributed to higher outdoor temperature during the second monitoring period, which rises to 20.6°C, compared to the mean outdoor temperature of the first monitoring period, which rises to 15.6°C. When the outdoor temperature fell below 15 °C, a few windows were opened but this pattern became more frequent when the outside temperature rose above 15°C (Figure 16.1-16.8). The window opening behaviour of the occupants is influenced by two factors: first, their need to enhance the air quality of the indoor environment and second, to make the space cooler by reducing indoor temperature and producing air movement. Occupants do not tend to open windows during the heating period and if they do so, it is rather for the need to improve indoor air quality. Based on Figures 16.1-16.8, during the heating period (07.30-10:00), windows are rarely opened leading to a high $CO_2$ concentration which exceeds the limit (Thursday and Friday). The effectiveness of ventilation is also made evident in Figures 16.1-16.8. One window, or a door, if opened can maintain IAQ during occupied time. Through on-site observation, it was observed that once windows are opened, they remain open until occupants feel discomfort. Closing a window indicates an act of eliminating environmental discomfort related to indoor temperature.

For example, Figure 16.1 shows that classroom on Wednesday remained opened throughout the day with a window opened till 10:05 and with three windows opened till the end of the teaching day maintaining indoor air quality. However, on Thursday, the same classroom remained closed in the entire day as the indoor air temperature is slightly lower reaching values of $CO_2$ concentration above the limits. During Friday, the classroom remained closed till 12:50 reaching values up to 3000ppm, while, during the occupation of the last teaching period, a door opened, as the indoor temperature is within the thermal comfort zone, maintaining the $CO_2$ concentration below the limits.

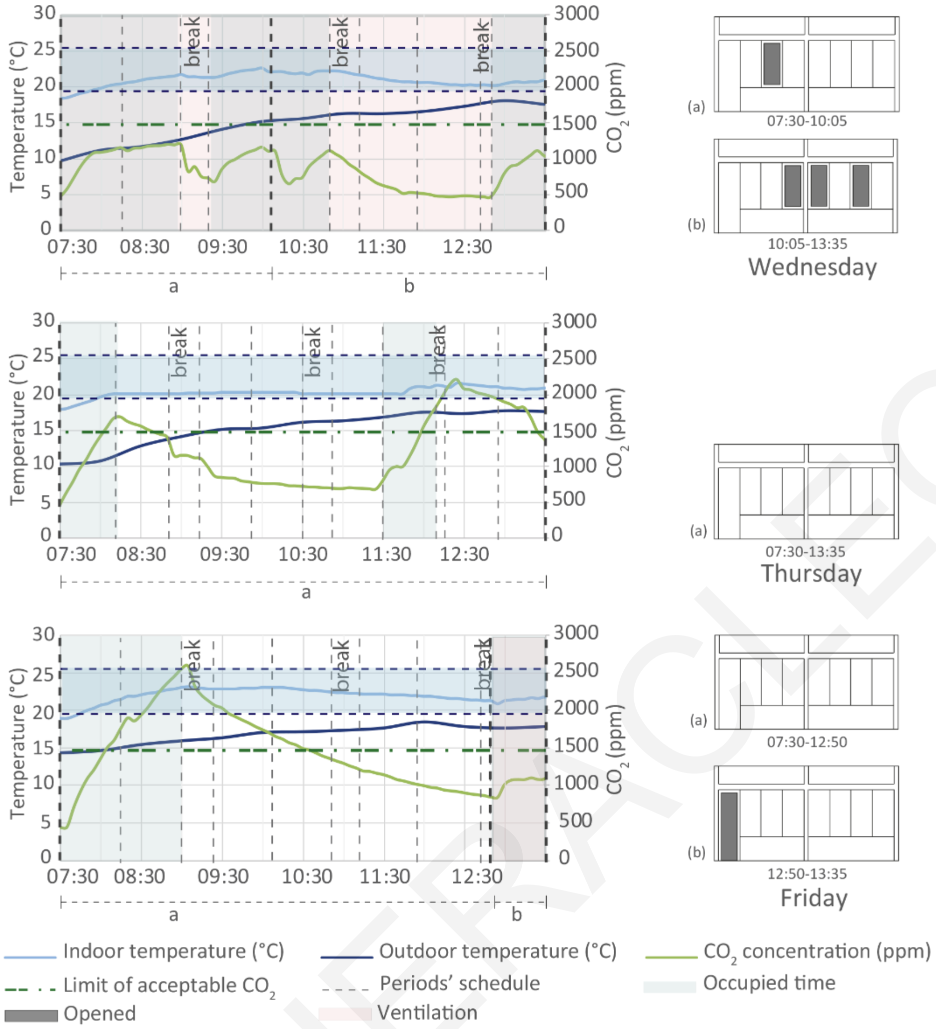



Figure 16.1. Free pattern of ventilation in classroom R1 during the first monitoring period, 14th of February - 16th of February 2018.

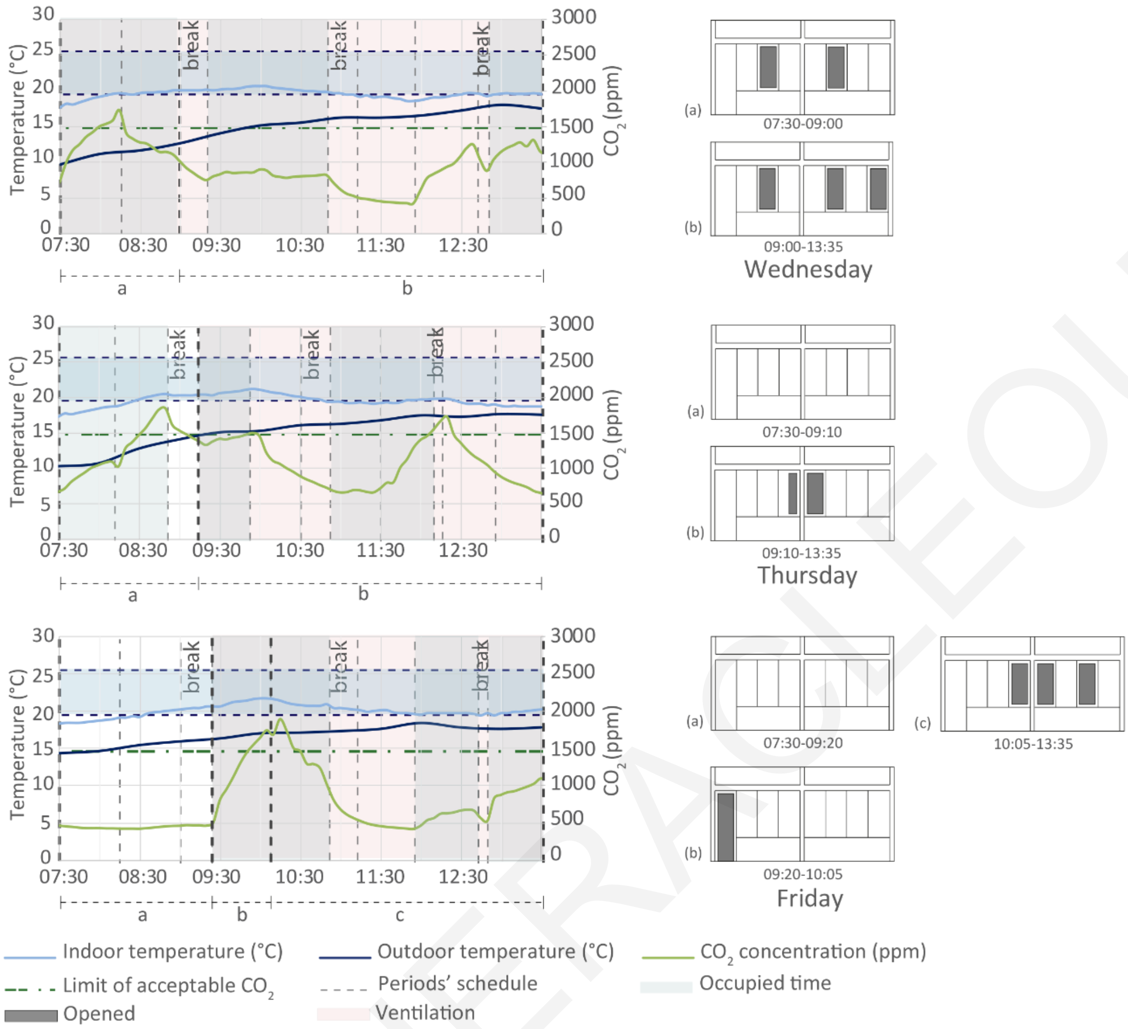



Figure 16.2. Free pattern of ventilation in classroom R2 during the first monitoring period, 14th of February - 16th of February 2018.

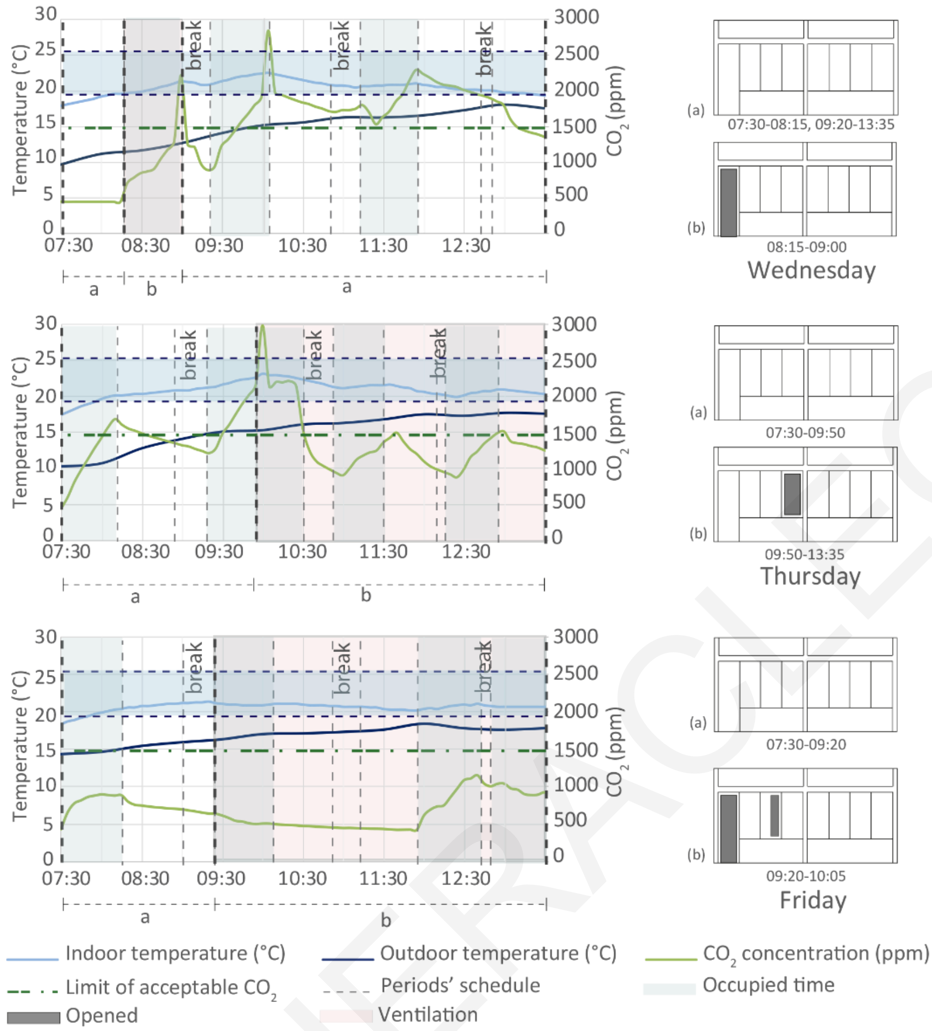



Figure 16.3. Free pattern of ventilation in classroom R3 during the first monitoring period, 14th of February - 16th of February 2018.

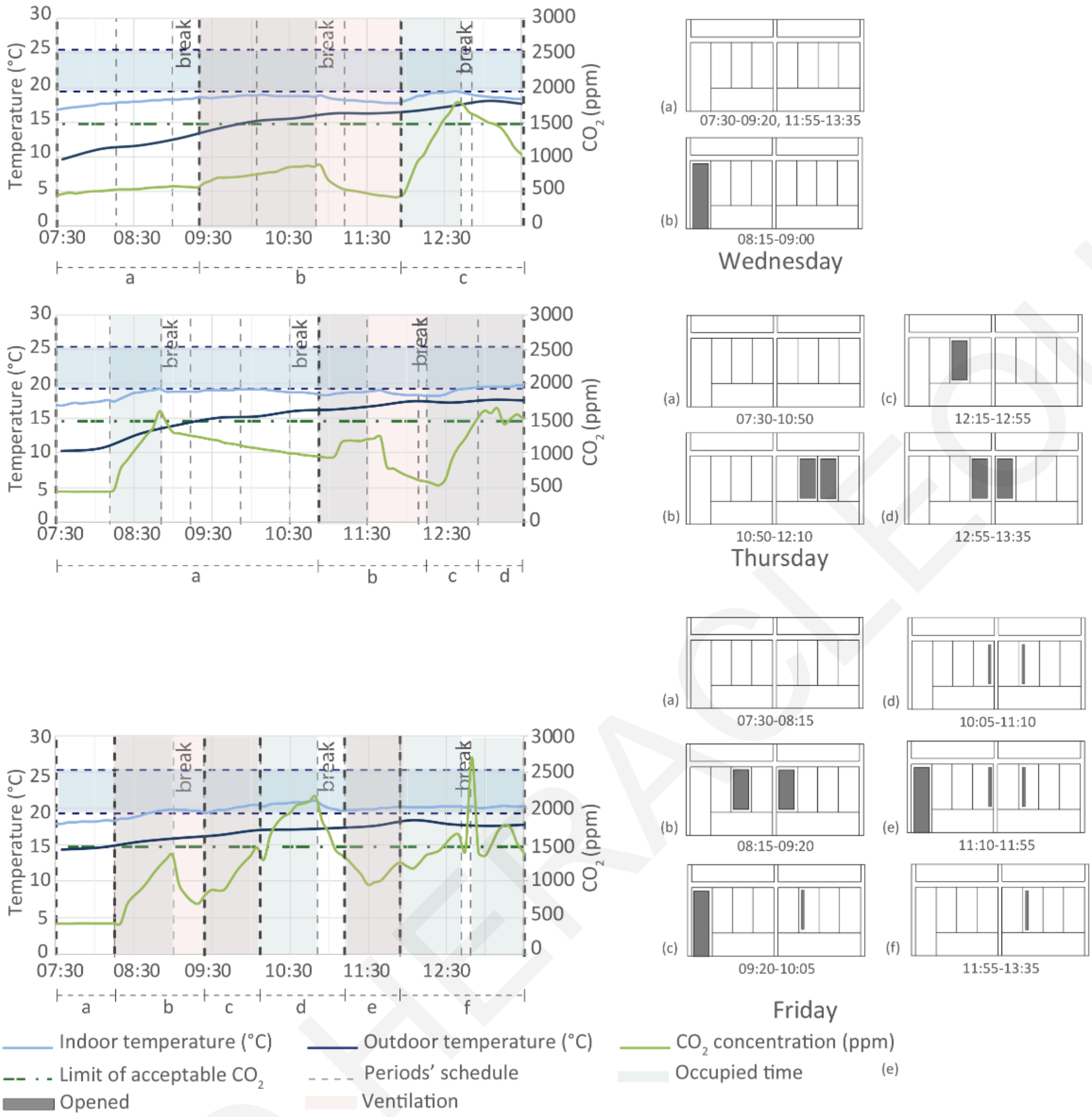



Figure 16.4. Free pattern of ventilation in classroom R4 during the first monitoring period, 14th of February - 16th of February 2018.

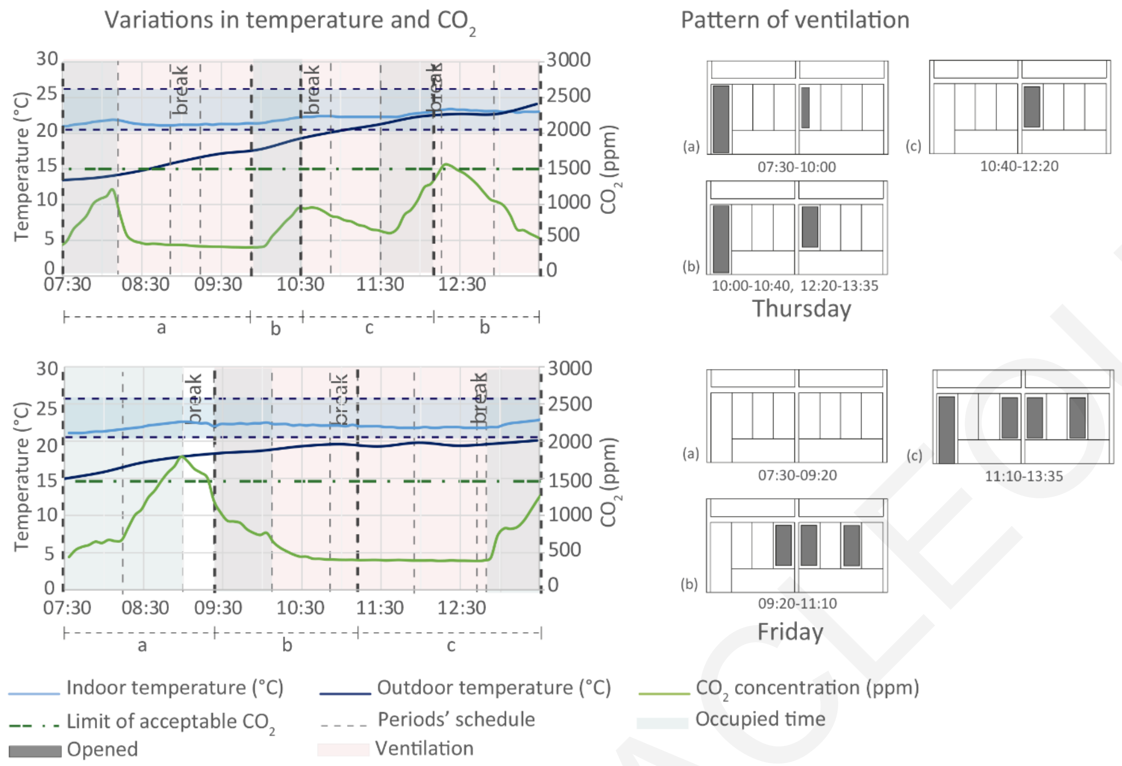



Figure 16.5. Free pattern of ventilation in classroom R1 during the second monitoring period, 8th of March -9th of March 2018.

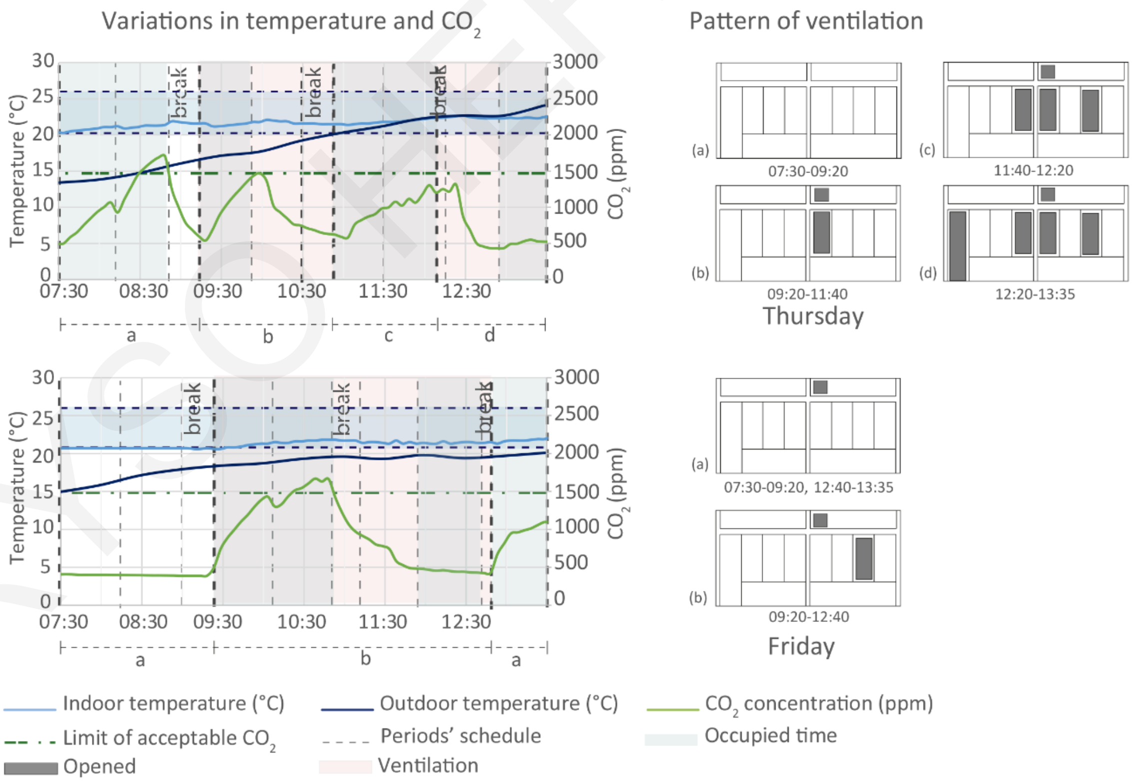



Figure 16.6. Free pattern of ventilation in classroom R2 during the second monitoring period, 8th of March -9th of March 2018.

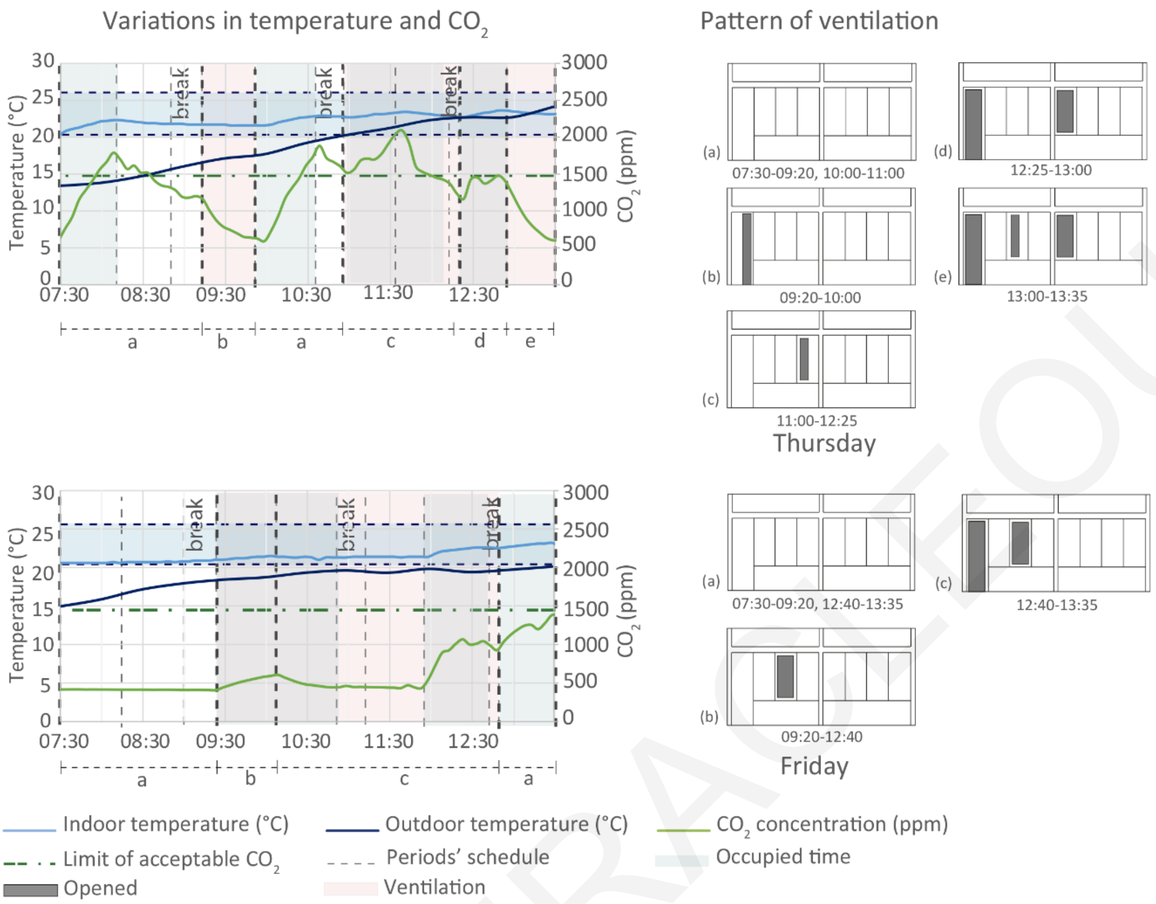



Figure 16.7. Free pattern of ventilation in classroom R3 during the second monitoring period, 8th of March -9th of March 2018.

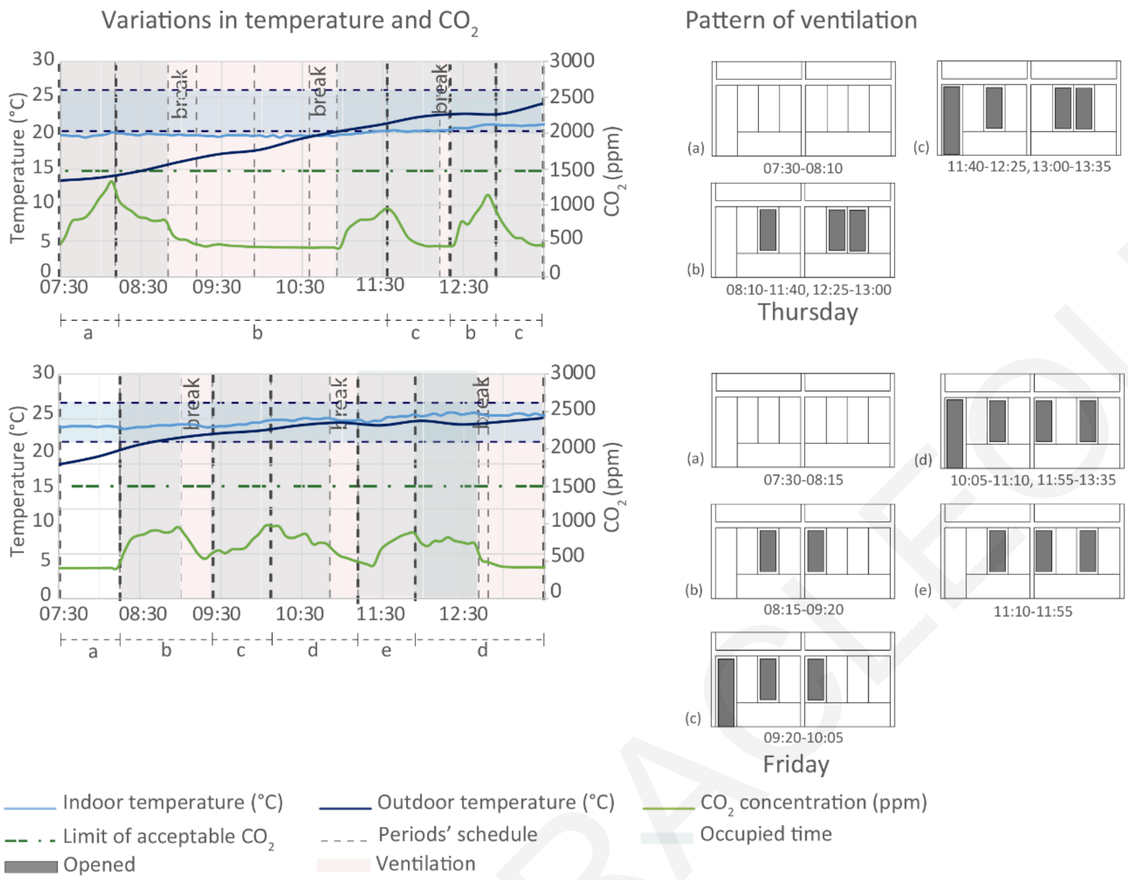



Figure 16.8. Free pattern of ventilation in classroom R4 during the second monitoring period, 8th of March -9th of March 2018.

*16.2.1.2. Recording period from the 16th of May to the 18th of May, 2018, Summer period.*

Peak values of $CO_2$ during the summer-time monitoring reached approximately 1800ppm in only one classroom (R3) during the morning periods, while others reached about 1300 ppm (Table 16.1). Again, the window opening behaviour of the occupants is influenced by their need to enhance the air quality of the indoor environment and to make the space cooler by reducing indoor temperature and producing air movement. One window or a door when opened can maintain $CO_2$ concentration below 1500 ppm during occupied time. It is worth mentioning that once windows are opened, they remain open until the end of the teaching day to maintain air movement and air quality. Closing a door is probably an action performed by the teacher to eliminate distraction of students and noise (Figure 16.9-16.12).

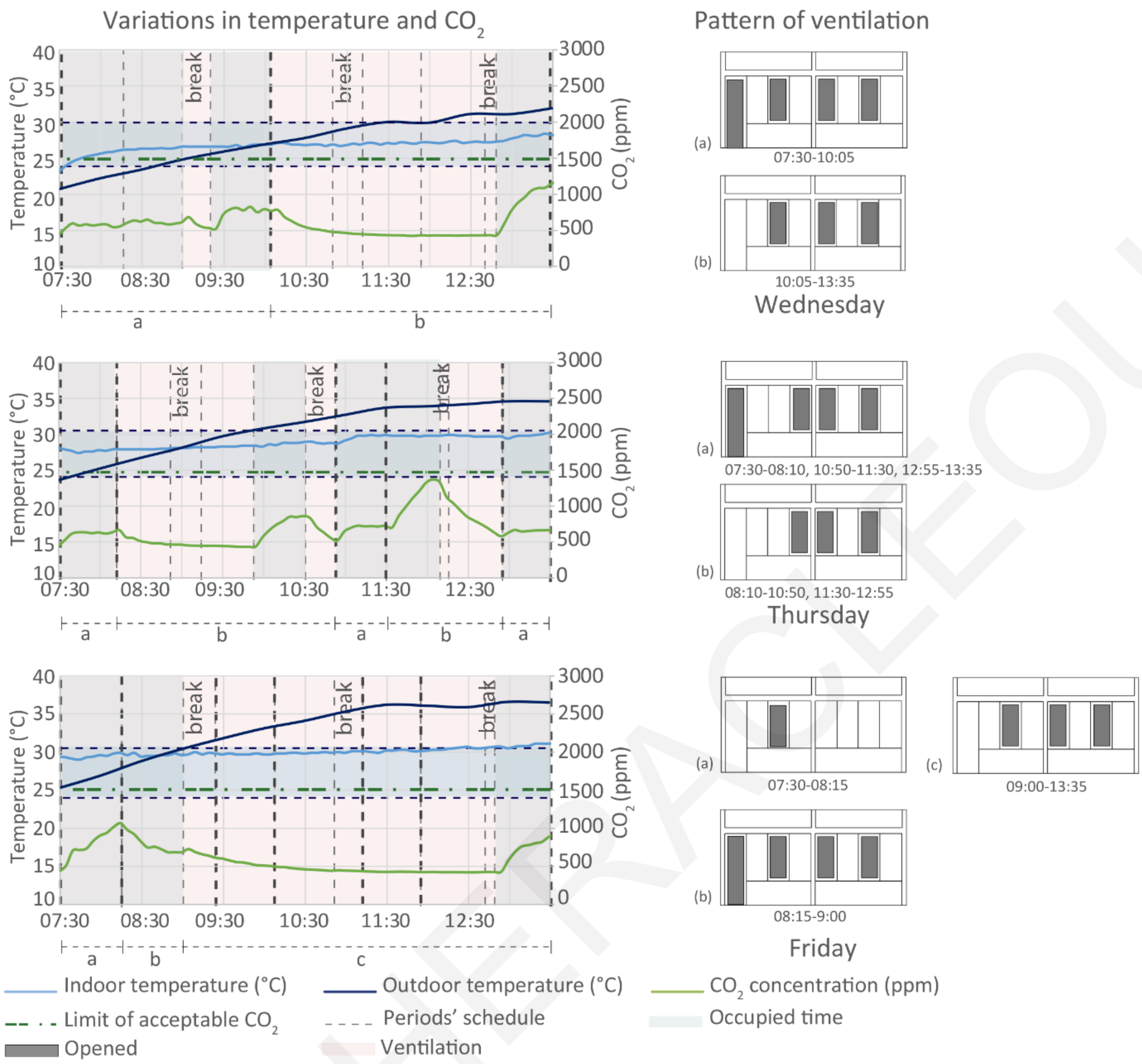



Figure 16.9. Free pattern of ventilation in classroom R1 during the third monitoring period, 16th of May -18th of May 2018.

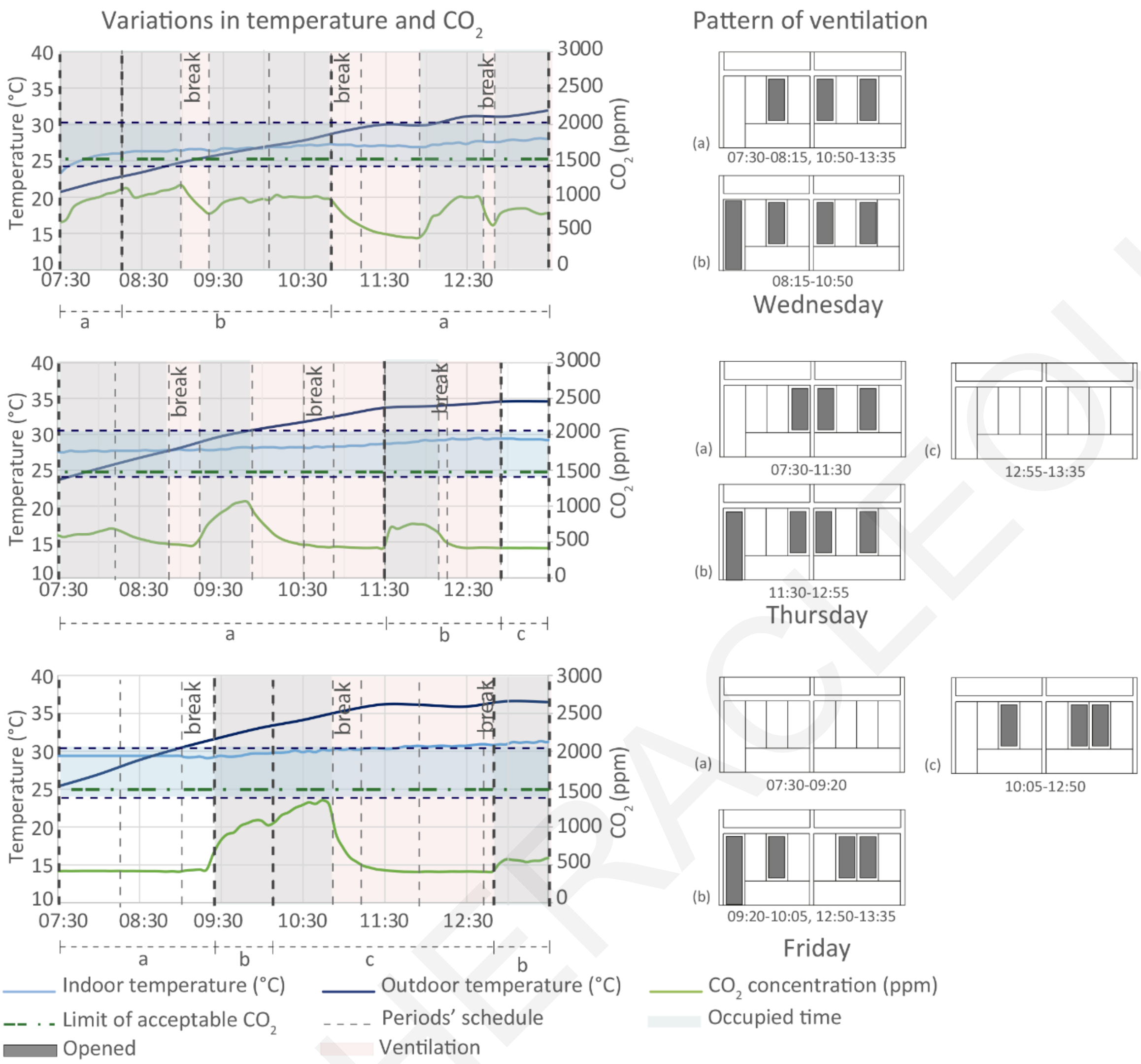



Figure 16.10. Free pattern of ventilation in classroom R2 during the third monitoring period, 16th of May -18th of May 2018.

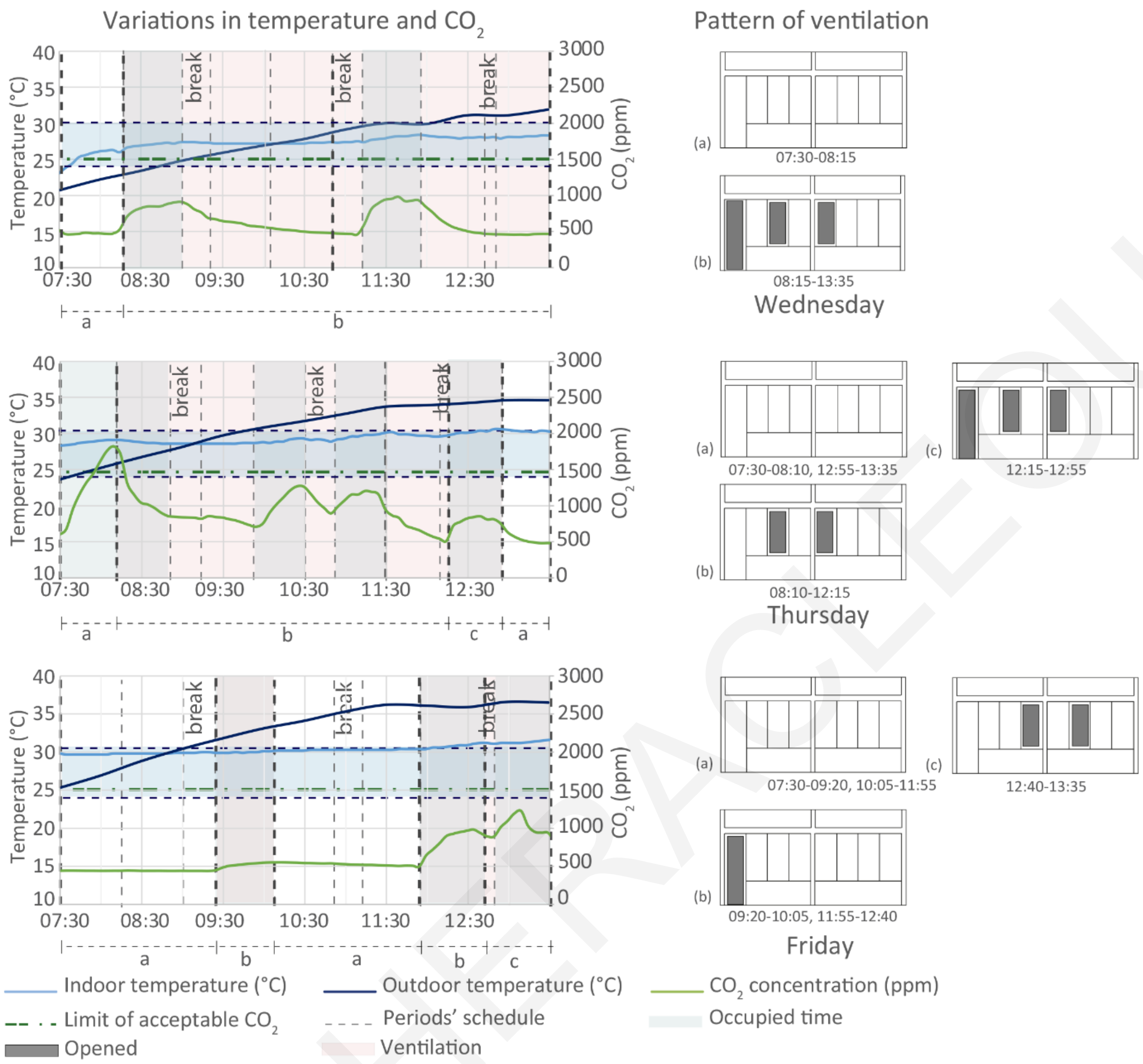



Figure 16.11. Free pattern of ventilation in classroom R3 during the third monitoring period, 16th of May -18th of May 2018.

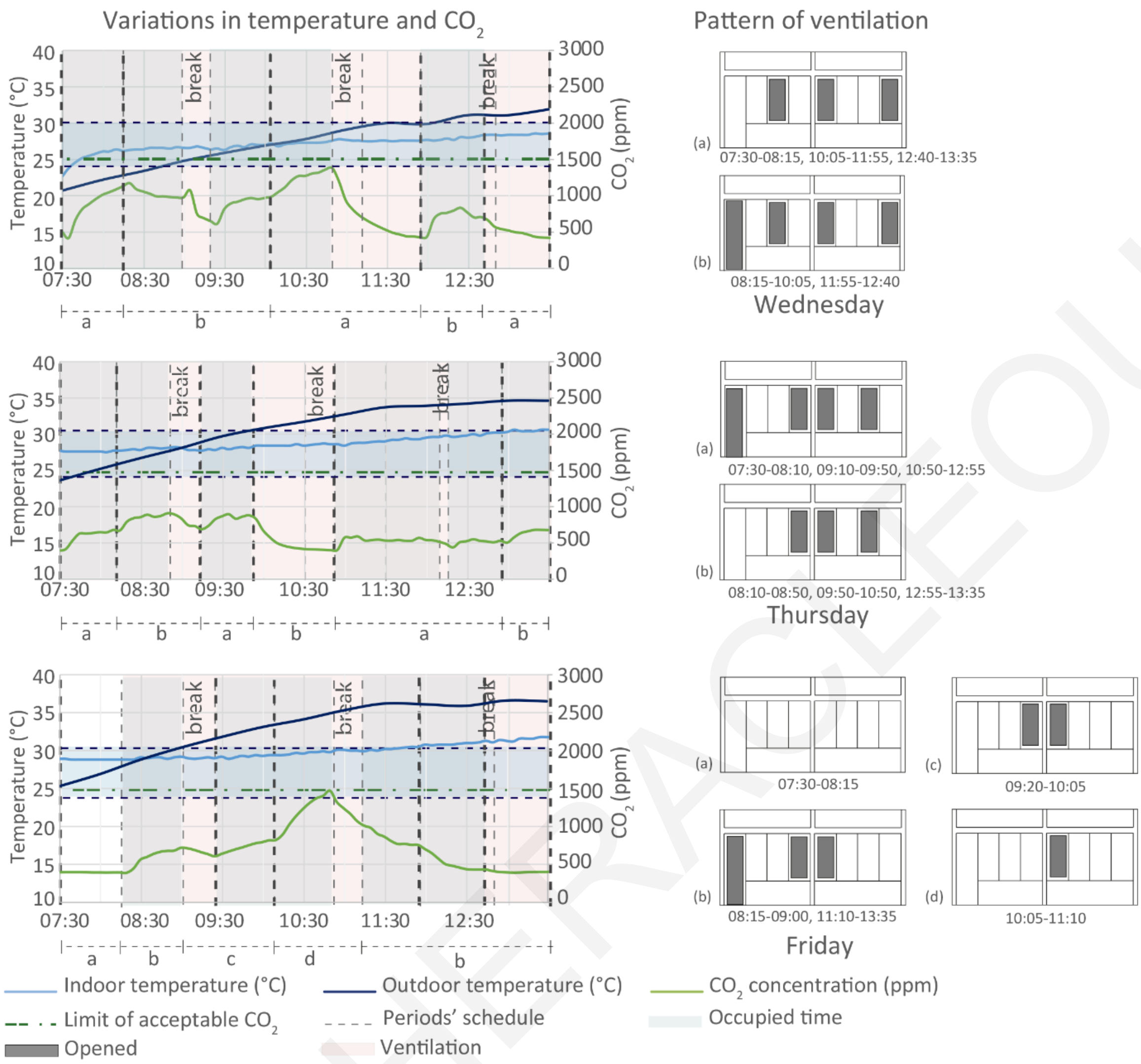



Figure 16.12. Free pattern of ventilation in classroom R4 during the third monitoring period, 16th of May -18th of May 2018.

### *16.2.2. Assessment of different ventilation strategies and window opening patterns on indoor air quality*

Various ventilation strategies and window opening patterns were examined in order to identify the best option to exploit natural ventilation as a means to achieve optimum air quality, especially during wintertime. The methodology of quantitative study through field measurements was described in **Chapter 12.2.** The data was recorded for both weekdays and weekend. The experiment was conducted in three periods, where the second follows some observations made in the first period. Both $CO_2$ concentration and comfort variables in the building were correlated with the standards. The proposed improvements will provide knowledge relevant to the exploitation of natural ventilation [494] while increasing environmental awareness [495] amongst students and society in general, as schools comprise the most promising public building types to act as lighthouse projects. Students can experience the tangible improvements to the building envelope of classrooms and they can learn how to support energy savings and indoor air quality through responsible user behaviour [293], [294].

The recordings were compared between classrooms pointing out slight differences, probably because of the different vicinities of the devices from the wall and windows. Table 16.2 shows the external conditions only during occupied hours, i.e., 07:30-13:35 and presents a compilation of the indoor record values of the same period.

Table 16.2. Synthesis table of all the recorded values carried out for the investigation of the impact of natural ventilation on both thermal comfort and air quality in educational buildings.

| | | Minimum Values | | | | Maximum Values | | | | Average Values | | | | Standard Deviation | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Experiment Type - Period | Parameter | R1 | R2 | R3 | R4 | R1 | R2 | R3 | R4 | R1 | R2 | R3 | R4 | R1 | R2 | R3 | R4 | Ref. Values |
| **Different window opening frequency** | Room temperature (°C) | 17.4 | 16.9 | 17.3 | 16.4 | 22.0 | 21.1 | 21.4 | 20.5 | 20.5 | 19.3 | 19.7 | 18.4 | 1.1 | 0.9 | 1 | 0.7 | 19.4-25.4 |
| | Relative Humidity (%) | 47.9 | 50.2 | 49.5 | 57.9 | 59.6 | 67.7 | 66.1 | 71.8 | 54.6 | 58.3 | 55.6 | 64.7 | 2.6 | 2.9 | 1.7 | 3.4 | 30-70 |
| | $CO_2$ concentration (ppm) | 377 | 486 | 406 | 394 | 2669 | 3239 | 2087 | 2431 | 1328 | 1604 | 877 | 1047 | 521 | 667 | 342 | 479 | ≤ 1500 |
| 1st monitoring period (10.2.2018 – 13.2.2018) | External temp. (°C) | 10.9 | | | | 17.9 | | | | 14.4 | | | | 2.3 | | | | |
| | External RH (%) | 49 | | | | 83 | | | | 66.6 | | | | 11.1 | | | | |
| **Different ventilation strategies** | Room temperature (°C) | 19.7 | 19 | 19.7 | 18.3 | 24.6 | 22.4 | 23.6 | 22.6 | 22.8 | 21.4 | 21.9 | 20.7 | 1.1 | 0.5 | 0.9 | 0.8 | 20.2-26.2 |
| | Relative Humidity (%) | 41.2 | 36.0 | 43.3 | 37.8 | 70 | 73 | 68.9 | 77.7 | 55.6 | 55.2 | 58.4 | 60.3 | 3.9 | 5.9 | 3.6 | 6.4 | 30-70 |
| | $CO_2$ concentration (ppm) | 417 | 416 | 407 | 409 | 2841 | 2989 | 2477 | 2357 | 859 | 1872 | 901 | 1372 | 680 | 591 | 564 | 482 | ≤ 1500 |
| 2nd monitoring period (3.3.2018 – 6.3.2018) | External temp. (°C) | 13.1 | | | | 24.2 | | | | 20.6 | | | | 3.4 | | | | |
| | External RH (%) | 31 | | | | 95 | | | | 56.5 | | | | 15.7 | | | | |
| **Different ventilation strategies** | Room temperature (°C) | 29.6 | 27.5 | 29.1 | 28.7 | 33.5 | 32.4 | 32.7 | 33.7 | 31.7 | 30.4 | 31.1 | 31.2 | 0.61 | 0.8 | 0.6 | 0.8 | 24.3.2-30.3 |
| | Relative Humidity (%) | 23.5 | 24.2 | 27.1 | 24.1 | 46.5 | 52.0 | 53.8 | 49.9 | 34.9 | 36.1 | 40.0 | 36.0 | 4.5 | 5.5 | 4.9 | 5.4 | 30-70 |
| | $CO_2$ concentration (ppm) | 417 | 403 | 415 | 401 | 847 | 852 | 1412 | 810 | 546 | 510 | 594 | 496 | 88.7 | 109 | 198 | 77 | ≤ 1500 |
| 3nd monitoring period (19.5.2018 – 22.5.2018) | External temp. (°C) | 24.9 | | | | 36.2 | | | | 30.7 | | | | 2.9 | | | | |
| | External RH (%) | 20.0 | | | | 62 | | | | 36.5 | | | | 9.8 | | | | |

#### *16.2.2.1. 1st Monitoring using different window opening frequencies (winter period)*

In the first experimental monitoring period, single-sided ventilation strategies were examined for different times of the day, in four classrooms. The openings that remained fully opened were C and F (that is half of openable windows in single-sided). In Case 4 (R4), windows opened during all break times (08:50-09:10, 10:30-10:50 and 12:10-12:15), in Case 3 (R3), windows opened in the last two breaks, in Case 2 (R2), windows only opened during the last break in midday. In Case 1 (R1), all the openings remained closed, i.e., no ventilation was monitored, to be used as a reference scenario.

Figure 16.13 shows an overall view of the measured values of air temperature, relative humidity and concentration of carbon dioxide in different classrooms during the first experimental monitoring period for both weekdays and weekend. The results were presented in correlation with the external temperature and relative humidity, as these factors can significantly affect the indoor conditions. The limit of $CO_2$ concentration at 1500ppm and the 80% acceptability limit of temperature are marked by the green line and light blue shadowed area respectively. Moreover, the figure illustrates the period during which the classroom is supported by a technical heating system. Finally, the figure illustrates with light pink colour the period during which the classroom is ventilated.

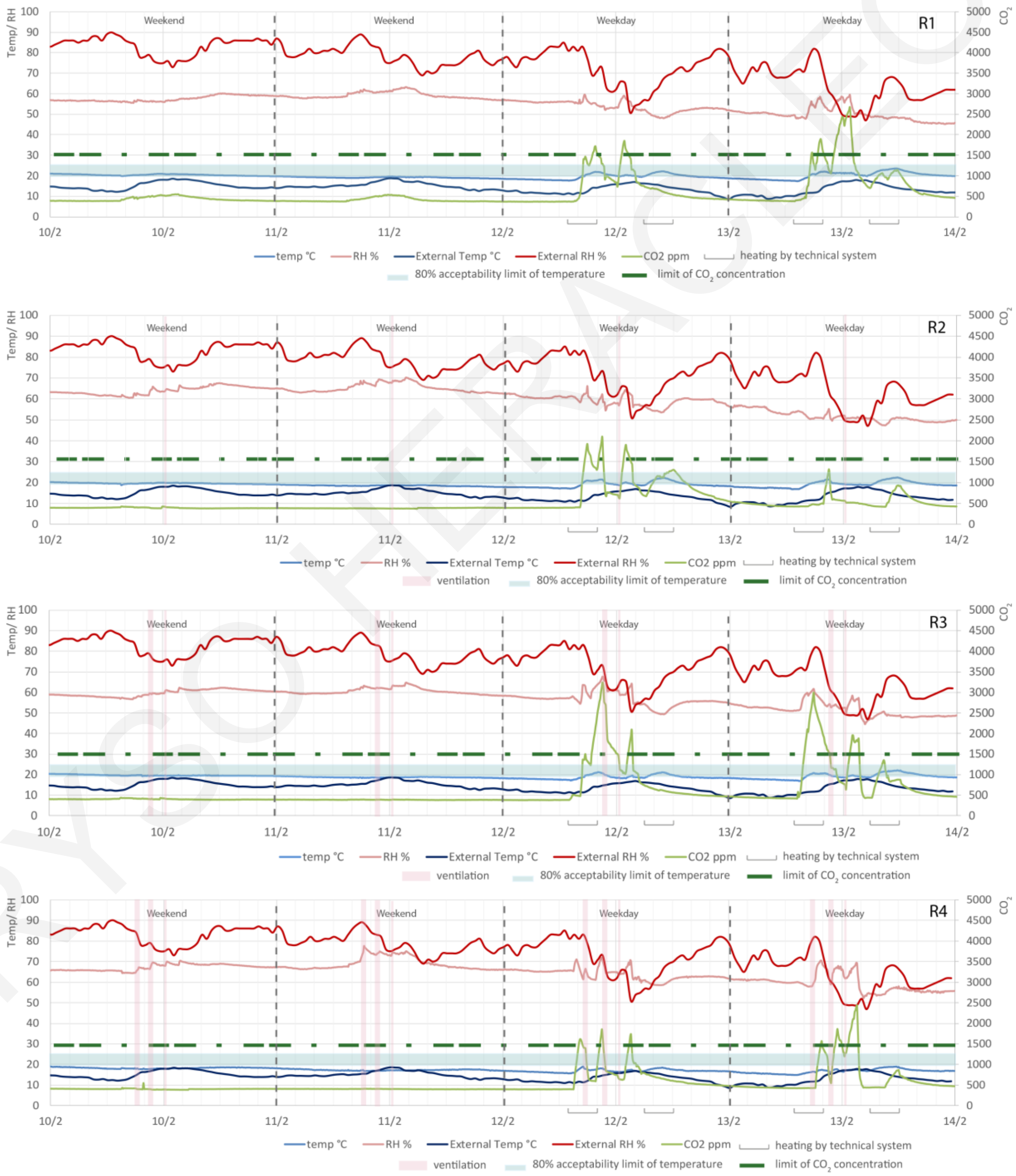



Figure 16.13. Indoor and outdoor temperature and relative humidity and indoor $CO_2$ concentration in classrooms R1-R4 for the 10th of February - 13th of February 2018.

According to Figure 16.13, $CO_2$ concentration levels during the weekend remain stable at about 420ppm while during weekdays, the IAQ parameters are not fulfilled despite the very high infiltration rate of 9.4 ach. During some mornings of occupied periods, $CO_2$ concentration values exceed 3000 ppm because the windows are closed during the teaching period to minimise heat losses. Nevertheless, Table 16.2 indicates that during the occupied periods, mean $CO_2$ values are not so high: varying between 877-1604 ppm with only one classroom (R2) exceeding the limit of 1500ppm. This is due to the fact that many classes remain unoccupied during the daily occupational period (07:30-13.35) which, in turn, results to lower mean values. As anticipated, the lowest values in all classrooms were recorded during night-time and early in the morning, during unoccupied time. During the afternoon session, the $CO_2$ concentrations were below the limit due to lower occupation density.

Considering that the monitoring process took place simultaneously in all classrooms, an immediate conclusion is evident in terms of temperature. Classroom R4 showed slightly lower temperatures compared to the others as it is more exposed to the external environment (Table 16.2). It is worth mentioning that the mean temperature values for classroom R2 and R4 were out of the reference interval (19.4-25.4°C) even though they were supported by technical heating, while classrooms R1 and R3 barely met the acceptability limit. The mean external temperature for the period of the first experiment is 14.4°C (Table 16.2). All recorded values of mean relative humidity met the norms (Table 16.2) and a maximum value of RH of 71.8% was only recorded in R4. It is notable that the indoor humidity trend in all classrooms showed an increase at the beginning of the occupied period (Figure 16.13).

The scenarios proposed in the first experimental monitoring period were investigating the possibilities of minimisation of heat losses coming from ventilation during the winter period. For that purpose, windows were closed during the teaching period while single-sided ventilation strategies were performed only during break time, for different times of the day in the four classrooms.

As indicated in Figure 16.14 and Figure 16.15, in an occupation period with 23-25 people, the $CO_2$ concentration reached the limit of 1500ppm and in most cases it even exceeded this limit. Specifically, in 15-20 minutes of occupation, the $CO_2$ increased above 1000 ppm (Figure 16.14a); while for two consecutive periods with users, the $CO_2$ concentration reached double the limit creating an unpleasant environment. The drop of $CO_2$ levels in all classrooms is associated with the students' departure from the classroom. However, if the classroom is unoccupied but closed, the reduction rate is slow (Figure 16.15b).

Looking at the "save energy" scenario (Case 1 in R1) according to which the windows are always closed during the daily occupational period, the $CO_2$ concentration is over 1500ppm. The 20-minute break, during which the class is unoccupied, does not lead to a reduction of $CO_2$ below 1000 ppm, leading to a further increase of $CO_2$ values during the coming occupied period and to poor air quality.

In a closed unoccupied classroom for one period (40 mins), the $CO_2$ concentration reduced from 1800 to 1300 ppm. Air temperature in R1 is the highest observed compared to other classrooms due to lesser heat losses through ventilation. A gradual temperature reduction of 1.5°C is observed by switching off the heating system.

Case 2 is also not effective in terms of indoor air quality as ventilation is provided only during the last 5-minute break when the heating system is switched off. As shown in Figure 16.14, a peak of 3000 ppm is reached, while two consecutive periods need approximately 3 hours of empty space to reach a value below 1000ppm. Indoor temperature fulfils the comfort conditions when heating by a technical system is provided; then temperature drops below the acceptability limit and again meets the limits at about 13:00.

Case 3 shows improved $CO_2$ concentration compared to Case 1 and Case 2. A provision of 20-minute single-sided ventilation during  the second break (10:30-10:50) reduced the $CO_2$ concentration by 1400ppm (from 2000ppm to 600ppm) without compromising thermal comfort and maintained air quality for the next periods. A small temperature drop is attributed to the switching off of the system. It seems that ventilation is required during every break time as the $CO_2$ concentration during the first break when the classroom is closed, remains high.

Finally, Case 4 exhibits the best performance concerning indoor air quality. The $CO_2$ concentration decreased by 54% from 1386 to 642 ppm due to ventilation provided during the first 20-minute break. Moreover, it further decreased by 44% from 1850 to 1000ppm during the second 20-minute break, leading $CO_2$ concentration below the limit target. The temperature dropped by about 0.5°C during the first 20-minute break (08:50- 09:10) while no variation was recorded compared to other classrooms during the ventilation provided in the second break.

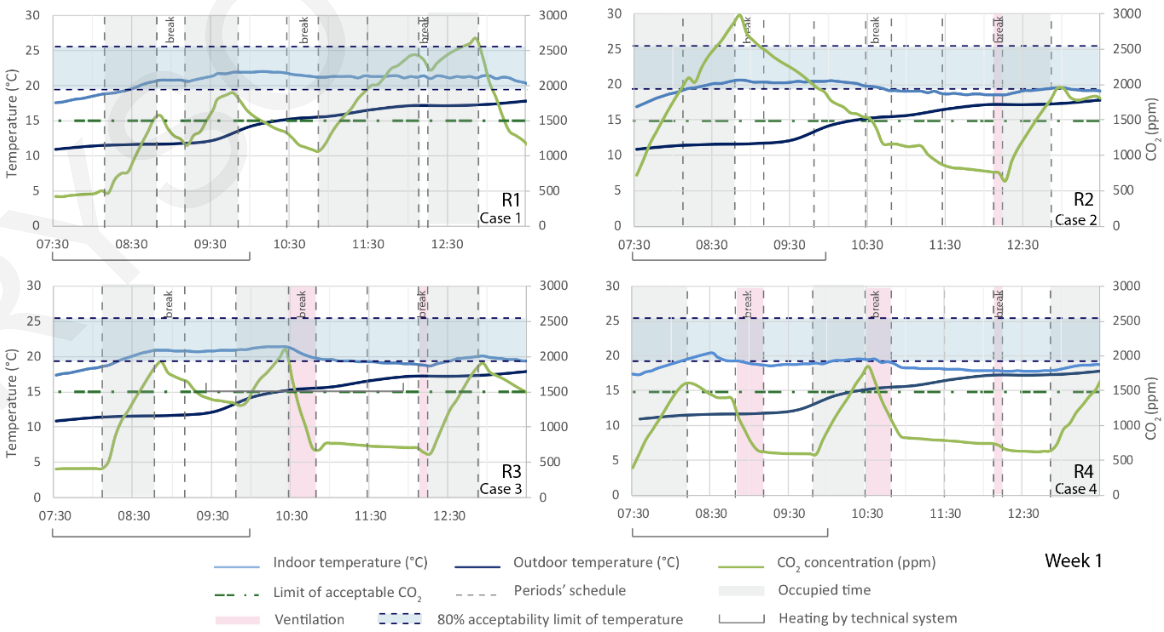



Figure 16.14. Indoor and outdoor temperature and CO concentration profile of classrooms under the experiments Case 1- Case 4 on  the $12^{th}$ of February 2018.

It should be noted that when the classroom is closed and unoccupied, the $CO_2$ concentration needs 9-12 hours to return to the normal levels of 420ppm, depending on the starting point (Figure 16.15b). This is attributed to the low airtightness level at 9.4 ach at 50Pa, as defined during the experimental procedure described in **Chapter 10.7.4.**

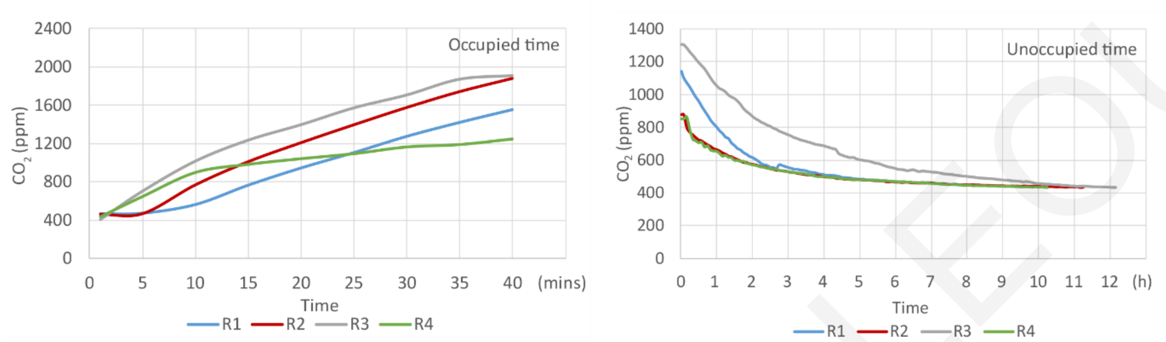



Figure 16.15. $CO_2$ concentration profile in all closed classrooms (a) during occupied time and (b) during unoccupied time against time.

*16.2.2.2. 2nd Monitoring using different ventilation strategies (winter –mild intermediate period)*

The results of the first monitoring period highlight the significance of improving classroom ventilation. As a next step, assessment of the effectiveness of different ventilation strategies in improving the ventilation rate in a way that would provide better indoor air quality in classrooms during the heating season was undertaken. Three situations were assessed: (a) single-sided ventilation with some windows open during break time (R3_Case 7), (b) single-sided ventilation with all windows open during break time (R1_Case 5), and (c) cross ventilation with some windows open during break time (R2_Case 6). Continuous ventilation is considered (R4_Case 8) because previous results showed high $CO_2$ concentration during the teaching period (Table 12.1).

Figure 16.16 shows an overall view of the measured values of air temperature, relative humidity and concentration of carbon dioxide in different classrooms during the second experimental monitoring period for both weekdays and weekend. The results were presented in correlation to the external temperature and relative humidity as these factors can significantly affect the indoor conditions. The limit of $CO_2$ concentration at 1500ppm and the 80% acceptability limit of temperature are marked by the green line and light blue shadowed area respectively. Moreover, the figure illustrates the period during which the classroom is supported by a technical heating system. Finally, the figure illustrates with light pink colour the period during which the classroom is ventilated.

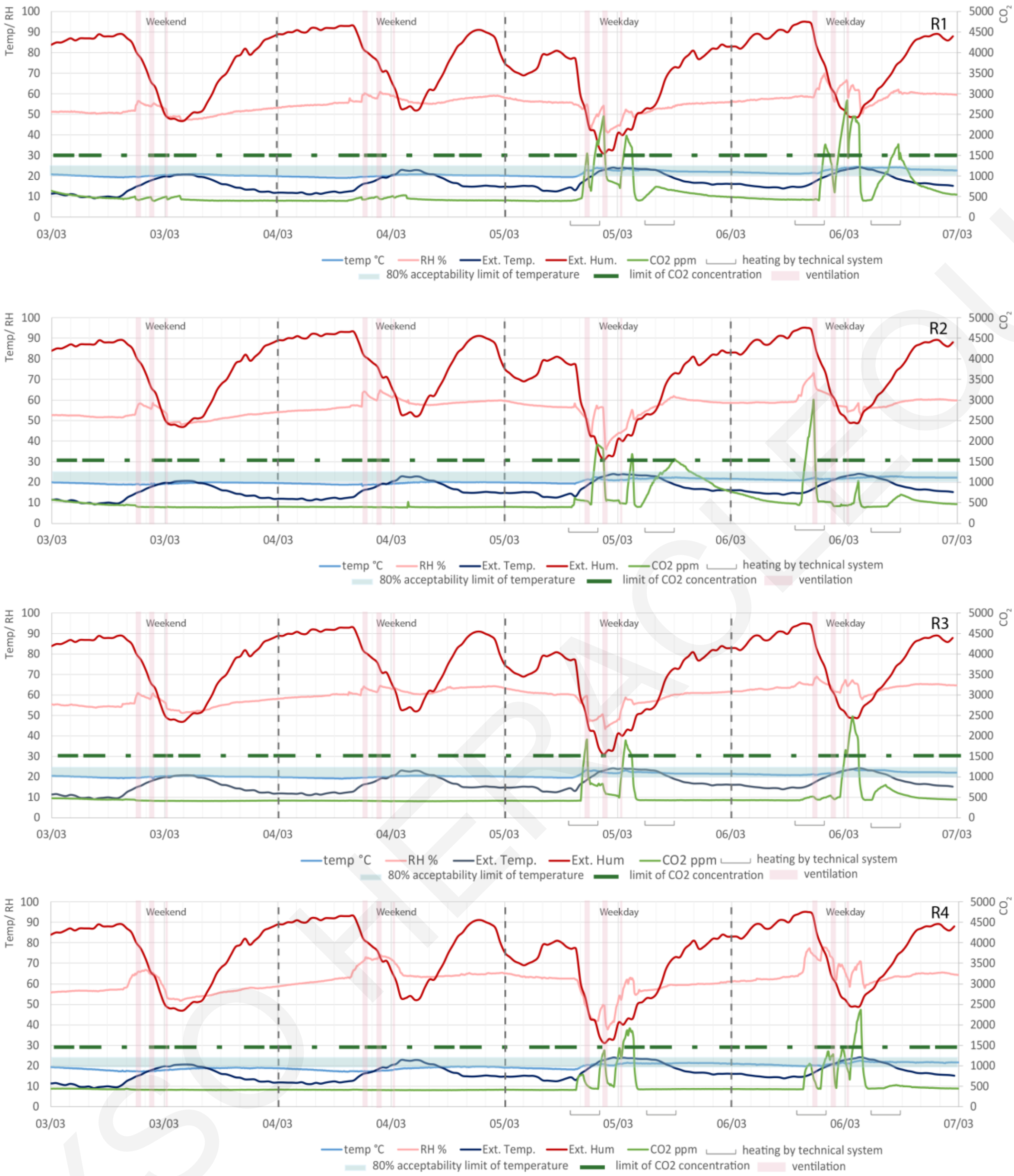



Figure 16.16. Indoor and outdoor temperature and relative humidity and indoor $CO_2$ concentration in classrooms R1-R4 for the 03rd of March - 06th of March 2018.

Average values of indoor air temperature during the second experimental monitoring period fall within the comfort zone. This is attributed to higher outdoor temperatures that reached a mean value of 20.6°C. In addition, the technical heating system enhances comfort between 07:00-10:00. All recorded values of mean relative humidity met the norms (Table 16.2.) but a maximum value of RH of 72% and 77% were recorded in R2 and R4 respectively as a result of the occupants' presence. It is notable that the indoor humidity trend in all classrooms showed an increase at the beginning of the occupied period (Figure 16.16).

$CO_2$ concentration in R1, R2, and R3, during occupied time, reaches values above 1000 ppm and in the case of two consecutive occupied periods, the $CO_2$ reaches values of 2500-3000 ppm. $CO_2$ concentration in classroom R4 is below the limit of 1500 ppm during the occupied time. This confirms the positive contribution of continuous ventilation during teaching periods. An increase occurs at the end of the day during the last two consecutive occupied periods where no adequate ventilation is provided in the preceding 5-minute break (Figure 16.17_R4). This means there is not enough time to reduce the $CO_2$ below 1000 ppm. The conclusion from this experiment is that the door alone cannot maintain IAQ when the classroom is consecutively occupied for two, or more, periods and when the ventilation provided before the occupation has a less duration than 20 minutes. In such cases, additional shorter-in-time ventilation openings should be considered during the teaching period.

The effectiveness of different ventilation strategies is presented in Figure 16.18. A 20-minute break is quite adequate to reduce $CO_2$ concentration. Cross ventilation (Case 6) gives a high ventilation rate causing a strong, quick fall of the indoor $CO_2$ followed by the case of single-sided ventilation combined with door opening (Case 8), followed by single-sided ventilation with all windows open (Case 5). The less effective strategy is the single-sided ventilation with some windows open due to the lowest ventilation rate (Case 7). Specifically, in a 20-minute break, Case 6 reduces $CO_2$ concentration from 3000ppm to 530ppm (82% reduction), Case 8 from 1270ppm to 460ppm (64% reduction), Case 5 from 2450ppm to 972ppm (61% reduction) and Case 7 from 1910ppm to 815ppm (57% reduction).

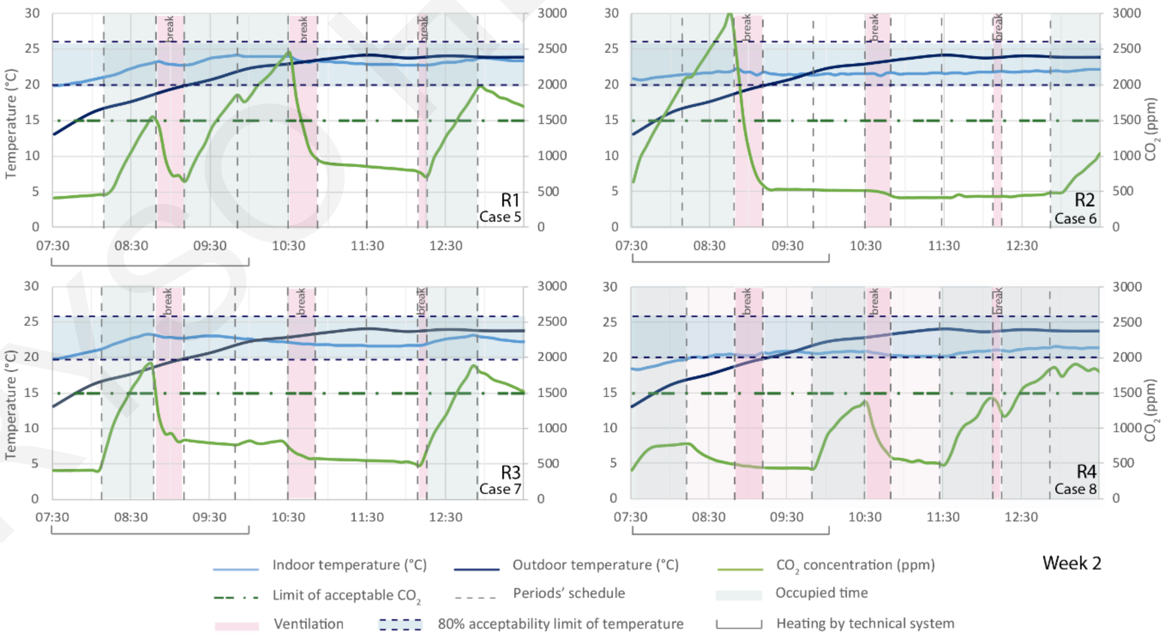



Figure 16.17. Indoor and outdoor temperature and $CO_2$ concentration profile of classrooms under the experiments Case 5 (single-sided with all windows opened during break-time), Case 6 (cross ventilation during break-time), Case 7 (single-sided with some windows opened during break-time) and Case 8 (single-sided with some windows opened during break-time and the door continuously opened daily) on the 6$^{th}$ of March 2018.

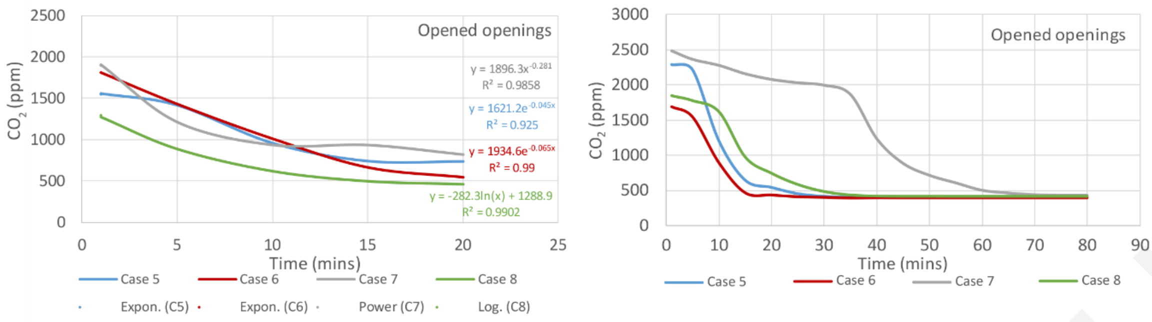



Figure 16.18. Effectiveness of different ventilation strategies (i.e. Case 5: single-sided with all windows opened during break-time, Case 6: cross ventilation during break-time, Case 7: single-sided with some windows opened during break-time and Case 8: single-sided with some windows opened during break-time and the door continuously opened daily) on $CO_2$ concentration reduction against time for two different break times in the four classrooms under study.

*16.2.2.3. 3rd Monitoring period using different ventilation strategies (summer period)*

During the third experimental monitoring period, the objective was to indicate the most effective cooling strategy, thus, both single-sided and cross-ventilation strategies were employed for different times of the day in the four south facing classrooms. Specifically, single-sided ventilation and cross-ventilation was proposed during the daytime, and cross-ventilation was proposed during the daytime as well as during the night time, and night time alone. Air quality during the summer period is not really an issue as increased ventilation is provided. In Case 1, single-sided daytime ventilation occurs in the morning hours, i.e. 07:00-13:30. For comparison reasons, in Case 4, cross-ventilation also occurs in the morning hours, i.e. 07:00-13:30. In Case 2, cross-ventilation was proposed for both daytime and nigh time, i.e. 07:00-13:30 and 21:00-07:00 and in Case 3, the classroom remained closed during the teaching hours to reduce heat gains; however, the door (i.e. opening A) remained open throughout the day to maintain indoor air quality. Cross-ventilation is proposed during the night, i.e. 21:00-07:00, to reduce the extensive heat stored in the building envelope. It is noted that in all cases under study that employed night ventilation, the door of the classroom remained closed for safety reasons.

Figure 16.19 shows an overall view of the measured values of air temperature, relative humidity and concentration of carbon dioxide in different classrooms during the third experimental monitoring period for both weekdays and the weekend. The results were presented in correlation to the external temperature and relative humidity as these factors can significantly affect the indoor conditions. The limit of $CO_2$ concentration at 1500ppm and the 80% acceptability limit of temperature are marked by the green line and light blue shadowed area respectively. Moreover, the figure illustrates with light pink colour the period during which the classroom is ventilated.

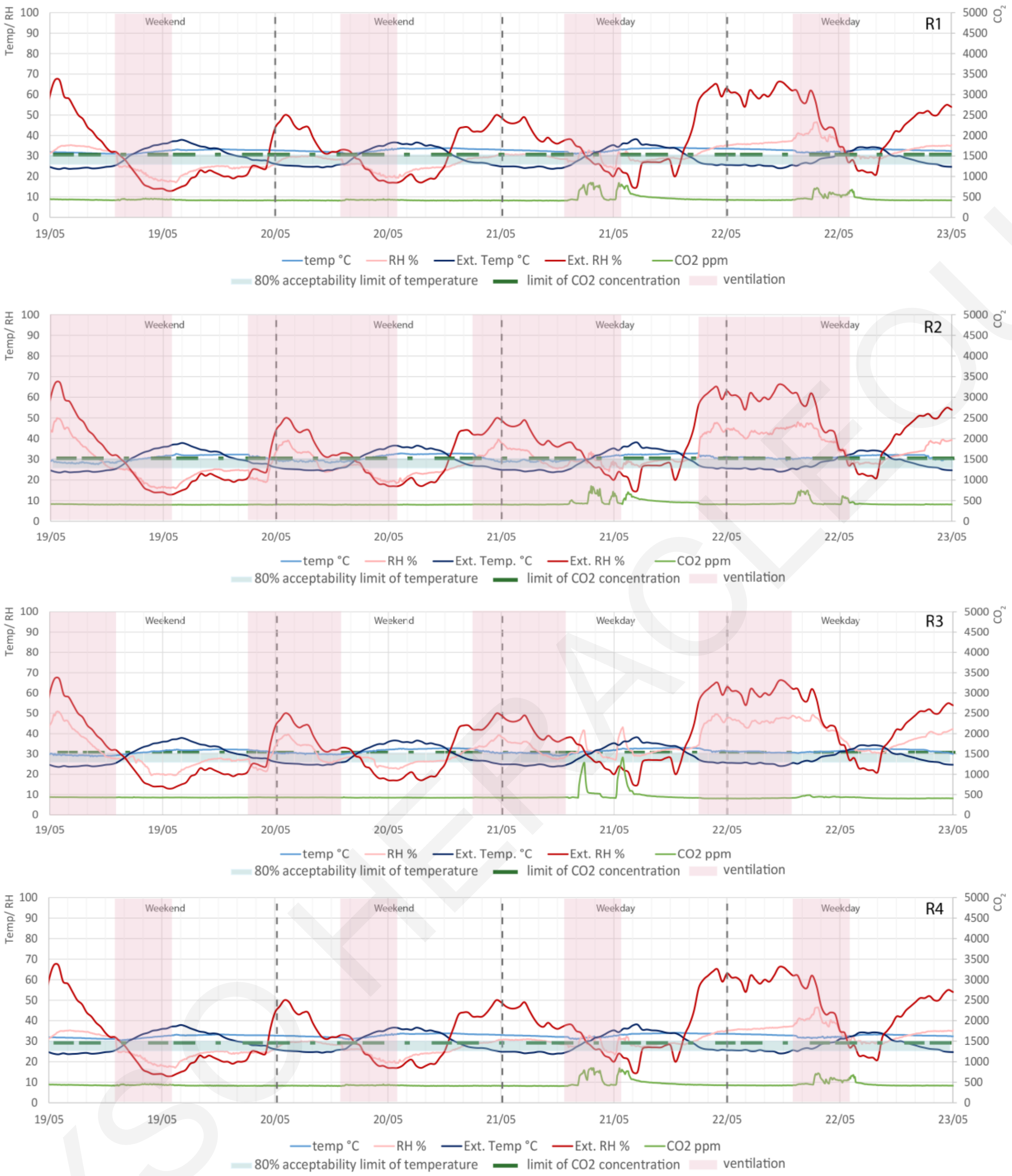



Figure 16.19. Indoor and outdoor temperature and relative humidity and indoor $CO_2$ concentration in classrooms R1-R4 for the19th of May - 22th of May 2018.

According to Figure 16.19, $CO_2$ concentration levels during the weekend remain stable at about 420ppm while during weekdays the IAQ parameters are met due to the different ventilation strategies. Classroom R3 shows the highest $CO_2$ concentration levels as it has the smallest ventilation rate during teaching period in order to minimize the heat gains. Nevertheless, Table 16.2 indicates that during the occupied periods, mean $CO_2$ values in all classrooms are not so high, varying between 496-594 ppm. This is connected with the fact that many classrooms remain unoccupied during the daily occupational period (07:30-13.35) which, in turn, results to lower mean values. As anticipated, the lowest values in all classrooms were recorded during night-time and early in the morning, during unoccupied time.

Considering that the monitoring process took place simultaneously in all classrooms, an immediate conclusion is drawn in terms of temperature. Classroom R2 showed lower temperatures compared to the others as it exploits night cooling in combination with cross ventilation during daytime (Table 16.2). It is worth mentioning that the mean temperature value for classroom R2 is the only one within acceptability limit, followed by classroom R3 which only incorporates night cooling. The worst-case scenario is classroom R1 which involved single-sided ventilation (the most usual ventilation strategy in educational buildings). The mean external temperature for the period of the first experiment is 30.7°C (Table 16.2). With regards to the relative humidity, the minimum values of relative humidity do not meet the limits (Table 16.2), however, the mean values are within the acceptable limits. It is notable that the indoor humidity trend in all classrooms showed an increase at the beginning of the occupied period (Figure 16.19).

An extensive study regarding the indoor thermal comfort through the monitoring investigation is described in **Chapter 14.2.**

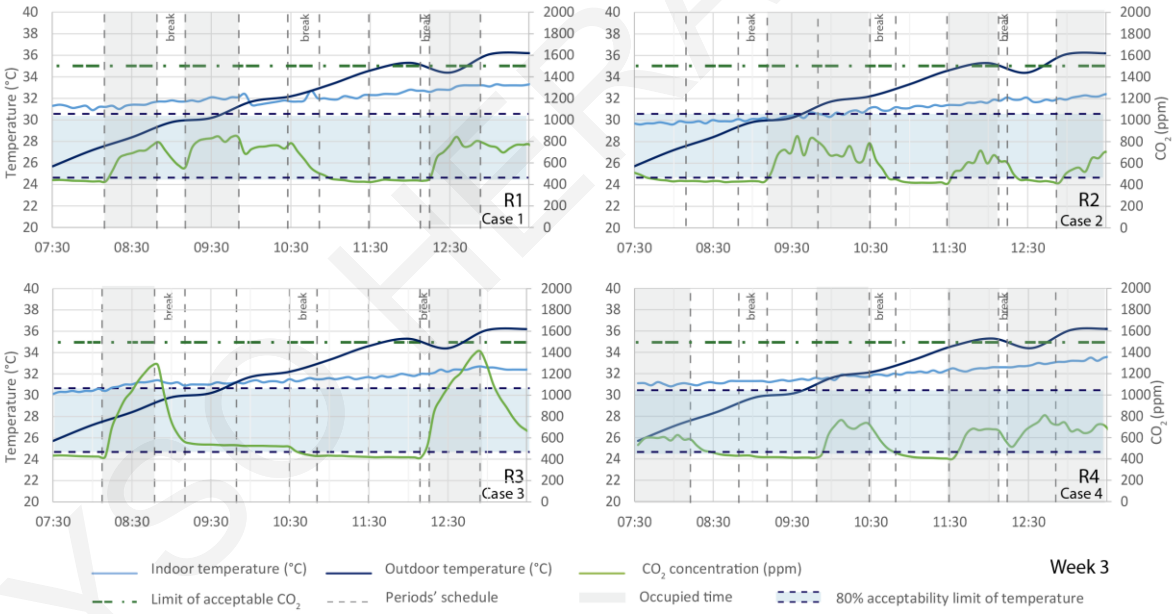



Figure 16.20. Indoor and outdoor temperature and $CO_2$ concentration profile of classrooms under the experiments Case 1 (single-sided during daytime), Case 2 (cross ventilation during daytime and night-time), Case 3 (cross ventilation during night-time, only door opened during daytime) and Case 4 (cross ventilation during daytime) at the 21st of May 2018.

$CO_2$ concentration in R1, R2, and R4, during occupied time was maintained below 1000 ppm during teaching period due to the increased ventilation rate at this period. $CO_2$ concentration in classroom R3, where only the door is opened during the teaching period is below the limit of 1500 ppm during the occupied time. As also observed from the previous experimental procedure, continuous ventilation during teaching periods through a door is important to maintain IAQ; however, attention should be given during the last two consecutive occupied periods where no adequate ventilation is provided in the preceding 5-minute break (Figure 16.20_R3) and therefore additional shorter-in-time ventilation openings should be considered during the last teaching period if occupied. As also observed from Fig. 16.8, cross ventilation during daytime (R4) is more effective than single-sided ventilation during daytime (R1) as the maximum, minimum and average values of $CO_2$ concentration are lower.

## 16.3. Results of subjective questionnaires regarding air quality

The findings of the questionnaire answered by the students and analysed using statistical programmes (Excel), are presented below. The methodology of qualitative study through questionnaires was described in **Chapter 12.3.**

The overall analysis of the air quality survey on dryness/dampness during the winter period shows that the occupants felt neutral or slightly dry, reflected in the mean values of -0.11. Specifically, 70.7% of students claimed to have a neutral feeling in terms of dryness (Figure 16.21). In terms of the freshness of air during winter, 51% of students voted that the air is fresh or almost fresh (i.e. point 1 and 2), however, 19.1% voted that it is heavy (i.e. point 4 and 5) resulting in a 2.5 mean value. Furthermore, 48.7% of students claimed that the air is odourless (i.e. point 1 and 2); however, 25.2% of students voted that they are is a strong smell (i.e. point 4 and 5) resulting in a mean value of 2.65. Concerning the air movement within the classroom, 44.3% of students voted that the air movement is ideal, while 46.5% of students voted that the air is still (i.e. point 1 and 2) resulting in a -0.50 mean value. Finally, 42.7% of students expressed the opinion that air quality levels are satisfactory or very satisfactory (i.e. points 1 and 2) but that the air quality is generally at moderate levels with a 2.73 mean value.

The overall analysis of the air quality survey on dryness/dampness during the summer period shows that the occupants felt neutral or slightly dry with mean values of -0.31. Specifically, 59.9% of students claimed neutral feeling in terms of dryness (Figure 16.21). In terms of the freshness of air during summer, the 47.9% of students voted that the air is fresh or almost fresh (i.e. point 1 and 2), however, 19.1% voted that it is heavy (i.e. point 4 and 5) resulting in a 2.58mean value . Furthermore, 56.7% of students claimed that the air is odourless (i.e. point 1 and 2); however, 14.7% of students voted that there is strong smell (i.e. point 4 and 5) resulting in a mean value of 2.37. Concerning the air movement within the classroom, 44% of students voted that the air movement is ideal, while 49.2% of students voted that the air is still (i.e. point 1 and 2) resulting in a-0.62 mean value. Finally, 40.1% of students expressed the opinion that air quality levels are satisfactory or very satisfactory (i.e. points 1 and 2), but that the air quality is generally at moderate levels with a 2.80 mean value.

It is interesting to mention that in the general question about comfort that was asking students what they do not like within the classroom, the unpleasant odours gained the largest percentage both in winter and summer (Figure 16.22).

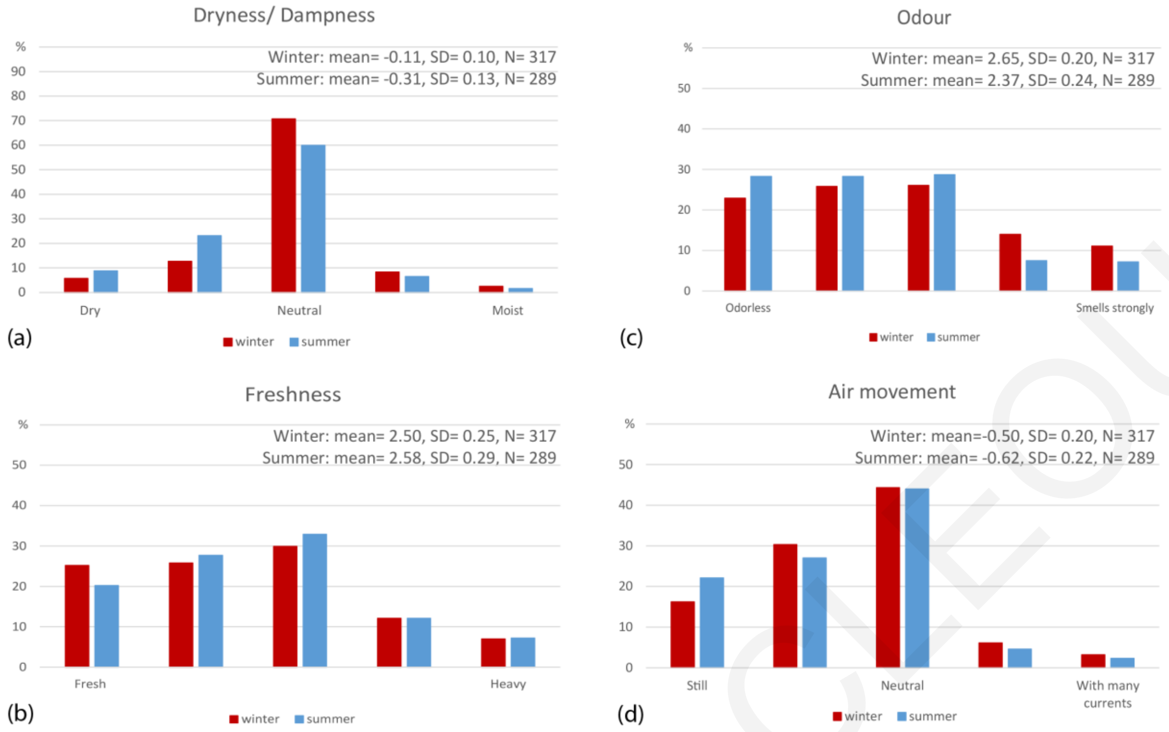



Figure 16.21. Percentage distribution of (a) dryness/dampness, (b) freshness (c) odour and (d) air movement votes during the summer and winter period.

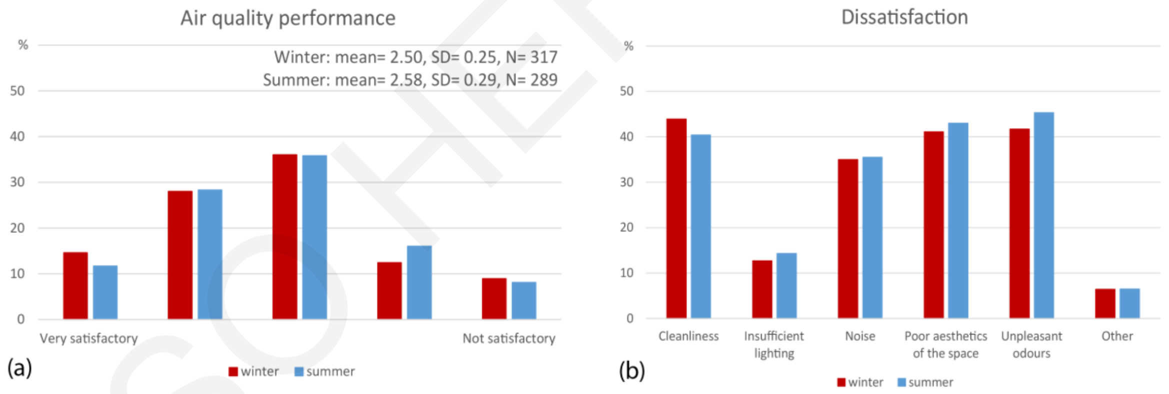



Figure 16.22. Percentage distribution of votes for overall air quality performance and dissatisfaction within the classroom.

## 16.4. Synopsis and Discussion

The study includes a comparative analysis of indoor air quality via the evaluation of concentrations of carbon dioxide as well as of thermal comfort conditions via operative temperatures of four south-oriented classrooms that adopted different ventilation strategies. The results highlight the effectiveness of an appropriate manual airing pattern. Moreover, they confirm that occupancy density, ventilation and window opening patterns largely affect the indoor air quality. Although airtightness of educational buildings is poor, $CO_2$ concentration levels are found to be exceeding the limit defined by standards when the classrooms are closed and occupied for two, or more, consecutive periods. This is in line with research studies in other Southern European countries, i.e. Italy, and

Portugal, that investigated the thermal performance of classrooms with similar typological and construction features. The studies conclude that when outdoor air temperatures drop, the teaching staff and students tend to leave windows closed and consequently ventilation rates fall leading to poor indoor air quality. The ventilation experiment of this study has shown that the ventilation of classrooms is necessary during every break time to reduce concentration and preserve air quality (Case 4-winter period). This is also reported in the study of Coley and Beisteiner [267] who concluded that opening windows between classes could reduce $CO_2$ levels and other contaminants to acceptable limits. The results are also in line with the study undertaken by Griffiths and Eftekhari [268] who monitored a UK school during the heating period and concluded that a 10-minute purge ventilation can reduce $CO_2$ concentration by approximately 1000 ppm without compromising thermal comfort. However, continuous ventilation, with a smaller air change rate through one window, or door, is also necessary during occupied periods (Case 8-winter period) as the optimum results show in terms of air quality. The results analysis shows that cross ventilation during break time (Case 6-winter period) leads to the quickest fall of $CO_2$ concentration compared to single-sided ventilation with some, or all, openings open, making it preferable at break time during heating season. During the experimental procedure in the summer period and the, all ventilation strategies maintain indoor air quality as are applied throughout the whole teaching period leading to an increased ventilation rate.

Based on the on-site observation and field measurements of free-pattern of windows, it was found that the correlation between the occupants' behaviour and window control is determined by the two most significant parameters: i.e., indoor $CO_2$ concentration and outdoor temperature. This is in line with early studies on residential ventilation which tried to predict window opening patterns through the use of environmental parameters employed as input variables. In their study, Dick and Thomas [496] and Santamouris et al. [266] established that outdoor temperature was, by far, the most significant variable which determined how many windows were opened. In a similar vein, Andersen et al. [497] studied 15 residential buildings and the probability of window opening and closing. Students' behaviour varies from classroom to classroom. However, in general, the results of the current study derived that classrooms are kept closed during the heating period as well as when the outdoor temperature is below 15°C which, in turn, leads to high $CO_2$ concentration levels. These results are consistent with the results of Nicol [498], who conducted surveys in the UK, Pakistan and throughout Europe about occupant behaviour and window operation. The proportion of open windows in European countries and Pakistan is generally lower than in the UK at any given temperature. However, it is noticeable that in all three surveys windows tend to be opened at a much higher rate when the outdoor temperature rises above 10°C. In a similar vein, in another Southern European country, i.e. Portugal, it was concluded that manual opening of windows provides appropriate ventilation for outdoor running mean temperatures larger than 19 °C, while for outdoor running mean temperatures between 16 and 19 °C, appropriate manual window-airing depends on the indoor air temperature. Finally, for outdoor running mean temperatures lower than 16 °C, manual window-airing becomes inappropriate [187].

Although window operation is considered mainly as an act that aims to alleviate thermal discomfort, in some cases, poor air quality caused by various odours also led students to window opening. This is also verified with the qualitative survey through questionnaires that indicated that students complain about odours within the classrooms and are not fully satisfied with the air quality. In these cases, windows remained open until occupants were in thermal discomfort due to low temperatures.

Moreover, the results derived from the current research show that outdoor environmental conditions affect indoor thermal comfort conditions greatly, as the indoor temperatures remain below acceptability limits during the majority of the occupied time in the winter period, despite the fact that a technical heating support is provided. The same performance is also observed during the summer period. This can mainly be attributed to poor air-tightness and lack of insulation of the building envelope, i.e., non-insulating load bearing elements, walls, floor and ceiling. During the weekends of the winter period, unoccupied and non-technically supported classrooms exhibited temperatures below the lower acceptability limit of the thermal comfort zone. In terms of mean relative humidity, it is noted that all the recorded values meet the norms except some moments during midday of summer days when the air is drier. Overall, all the above-mentioned issues demonstrate the need for building envelope improvements in educational premises, including thermal insulation and airtightness provisions. Finally, it should be noted that despite the fact that the poor airtightness of the building envelope has beneficial influence on the classrooms' indoor air quality it allows un-controlled infiltration which greatly affects the energy performance of the educational buildings during the heating period.

The analysis of indoor human comfort, as performed in the current study, has specific limitations deriving from the experimental character of the research. More specifically, the thermal comfort analysis was performed using the adaptive comfort standard, which assumes that indoor spaces are not supported by any technical system. However, in the current study, the classrooms were supported by a central heating system, which drastically affects the thermal performance of the spaces. To minimize the negative impact of this limitation, the evaluation of each ventilation strategy and window opening pattern was performed in a comparative manner. Additionally, for more accurate and precise results, the indoor human comfort conditions under different ventilation strategies and window opening patterns were also evaluated during weekends; periods without the operation of any heating system. However, it should be noted that although adaptive comfort model was used, the use of the heat balance method of PVM that sets a constant comfort zone at 20-26°C, when the building is supported by technical heating system, is very near with the adaptive comfort (0.5°C difference).

In the same framework, the number of occupants, which slightly varies from one classroom to the other, could affect the monitored indoor environmental data. Moreover, the presence of occupants during the monitoring periods leads to limitations in the application of particular ventilation scenarios, which could create entirely unsuitable indoor conditions.

Finally, although the indoor environmental parameters under study, i.e., $CO_2$ concentration and air temperature, are recognised among the most important determinants of window opening, they do not entirely guarantee acceptable indoor thermal and air quality conditions. Based on the existing literature, environmental parameters such as solar radiation, precipitation and relative humidity could also affect indoor human comfort and thus, window opening control.

# Chapter 17. Assessment of natural lighting performance and visual comfort of educational buildings and proposed improvements under current climatic conditions

## 17.1. Introduction

This chapter is organized into three main subdivisions to present the assessment of natural lighting performance and visual comfort as well as proposed improvements under current climatic scenarios. The multi-criteria methodology followed allows the holistic evaluation of the visual comfort conditions while it further safeguards the validity and reliability of the results. The first section of this chapter describes the results from the qualitative questionnaire field study tracing the occupants feeling about visual comfort. The second part reports the results of the simulations of a calibrated model using multiple evaluation criteria such as static and dynamic daylight performance metrics as well as glare metric. The third section proposes potential improvements in order to provide better visual conditions, in terms of both lighting levels and glare issues, and to minimize the energy consumption due to the use of artificial lighting. Finally, a synopsis and discussion and a chapter summary are provided.

## 17.2. Analysis of qualitative questionnaire field study

A qualitative assessment of the visual comfort in a typical classroom is achieved through field study research. The methodology of the qualitative study, through questionnaire, was described in **Chapter 13.3.** The results of the questionnaire-based survey, provided by participants on a seven-point Likert scale, are analyzed below. The majority of students and teachers (n=39 teachers; n=326 students), i.e. 82.5% and 83.0% respectively, evaluated natural lighting, in terms of brightness and darkness, as *sufficient* or *almost sufficient* (indicated as points 03, 04 and 05 on Figure 17.1a). In terms of lighting uniformity, 53.0% of students (n=211), and 48.9% of teachers (n=23) characterized natural lighting as *partially uniform* or *partially non-uniform* (i.e. points 03, 04 and 05 on Figure 17.1b). Furthermore, in terms of glare, 34.5% of the students (n=138) claimed extensive *glare issues* (i.e. points 06 and 07 on Figure 6c) and 39.0% of the students (n=156) for *partial glare issues* (i.e. points 03, 04 and 05 on Figure 17.1c). However, it should be noted that 51.1% of teachers (n=24) claimed *no glare* or *almost no glare issues* (i.e. points 01 and 02 on Figure 17.1c). The differentiation in the answers indicates that glare issues are caused from direct impingement of the sun's rays to the task surfaces, i.e. students' desks and classroom writing boards. Regarding an overall evaluation of natural lighting levels, a significant percentage of students and teachers, i.e. 49.0% (n=196) and 66.0% (n=31) respectively, claim an *average* natural lighting performance (i.e. points 03, 04 and 05 on Figure 17.1d). In addition, 41.5% of students (n=166) and 29.8% teachers (n=14) express the opinion that natural lighting levels are *satisfactory* or *very satisfactory* (i.e. points 01 and 02 on Figure 17.1d).

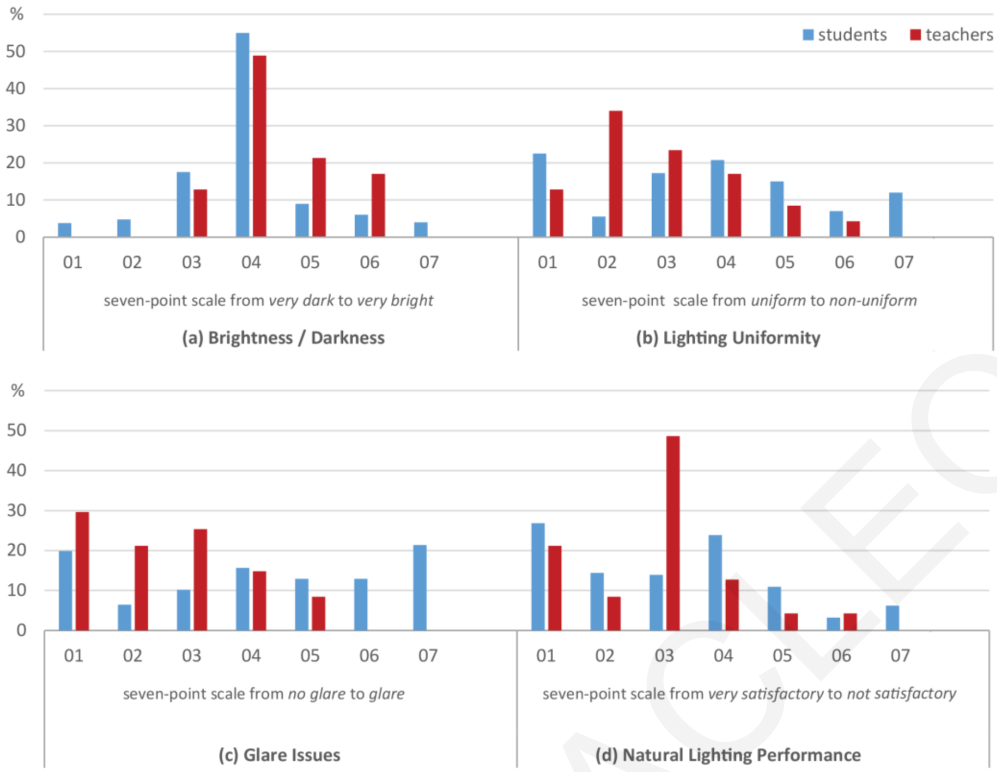



Figure 17.1. Graphic representations of the results of the questionnaire-based survey of natural lighting evaluation in terms of (a) brightness / darkness, (b) lighting uniformity, (c) glare issues and (d) natural lighting performance.

Finally, the results of the questionnaire-based survey in terms of the periods of year and times of day that artificial lighting is used are presented in Figure 17.2. Based on the results analysis, artificial lighting is used during the entire year at all working hours of the day, indicating that curtains are kept closed, most probably to control glare and over lighting problems.

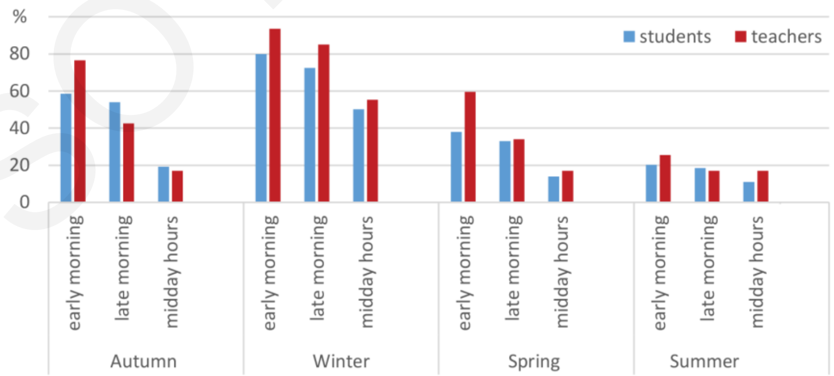



Figure 17.2. Graphic representation of the results of the questionnaire-based survey in terms of the periods of year and times of day that artificial lighting is used.

## 17.3. Analysis of lighting simulation

### *17.3.1. Analysis of Static and Dynamic Metrics*

The methodology of the quantitative study through software simulation was described in **Chapters 14.4-14.6.** The analysis of the simulated results is divided into two parts. The first part includes the static daylight performance metric, while the second part considers the dynamic daylight performance metrics. The rendering parameters were imported from Radiance in Daysim v.3.1 software and are presented in Table 17.1. The spaces under study were set as occupied during weekdays, i.e. Monday through Friday, from 7:30 to 13:30. The simulation for the building assumes the daylight saving time from the 1st of April to the 31st of October.

Table 17.1. Simulation parameters for Daysim analysis

| Ambient bounces | Ambient divisions | Ambient samples | Ambient Accuracy | Ambient Resolution | Direct Threshold | Direct Sampling |
|---|---|---|---|---|---|---|
| 5 | 1000 | 20 | 300 | 0.1 | 6 | 0 |

*17.3.1.1. Static daylight performance metric*

The static daylight performance metric regards the Daylight Factor (DF) should be above 2% for 75% of the space area. The quantity of light under an overcast sky in all classrooms shows almost similar results. The east-orientated classroom, i.e. the classroom with the largest windows facing east, and the clerestories facing the opposite side, has slightly lower average DF with a value of 2.8%. Moreover, 83% of the space floor area shows DF above 2% achieving the daylight target. The uniformity criterion (Min DF/Average DF) was achieved with a value of 0.36 and a minimum DF of 1%. The west, south- and north-oriented classrooms achieve an average DF of 3% and the percentage of the space with DF above 2% is 86%. The west- and south-oriented classrooms provide slightly better uniformity compared to other orientations with a uniformity ratio of 0.40 and 0.43 respectively. The north-oriented classroom provides a uniformity ratio of 0.37 (Table 17.2).

Table 17.2. Average daylight factor and percentages (%) of space area with daylight factor above 2% for the base case scenario of spaces under study.

| Orientation | Average DF [%] | % of space DF > 2% | Min DF | Uniformity (Min DF/Average DF) |
|---|---|---|---|---|
| **East** | 2.8 | 83 | 1.0 | 0.36 |
| **West** | 3.0 | 86 | 1.2 | 0.40 |
| **South** | 3.0 | 86 | 1.3 | 0.43 |
| **North** | 3.0 | 86 | 1.1 | 0.37 |

*17.3.1.2. Dynamic daylight performance metric*

The results from the dynamic daylight simulation of the typical classroom under study for different orientations are shown in Table 17.3. Based on the DA index, classrooms in all four orientations demonstrate almost similar performance and can be characterized as well-lit spaces. Although the east-orientated classroom showed lower average DF under an overcast sky, it exhibits the higher DA average, while the lowest average DA is shown in the north-oriented classroom. Specifically, the east-oriented classroom meets the minimum illuminance threshold of 300 lux for 97.0% of the occupied hours of the year, while the north classroom achieves the threshold for 94.1% of the occupied hours of the year. The west- and south-oriented classrooms achieve the threshold for 95.7% and 95.3% of the occupied hours of the year respectively.

As shown in the Figure 17.3, the area of the classroom with the lowest lighting levels is the area in the proximity of the clerestories, while, the area with the highest lighting levels is the area in the proximity of windows. The area in the centre of the classroom exhibits average lighting levels.

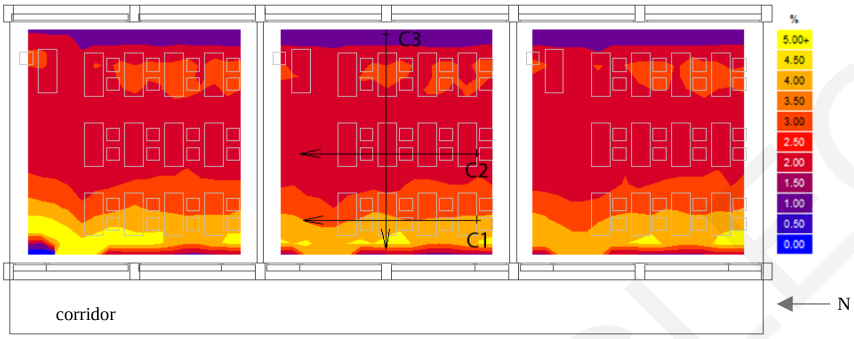



Figure 17.3. Lighting distribution of the daylight factor (DF) under an overcast sky in the west-oriented classroom. The entrance of the classroom is located in the bottom of the figure, from the corridor.

Based on the useful daylight illuminances (UDI), classrooms in all orientations have illuminance levels between 100 and 2000 lux for a significant part of the occupied hours of the year. The north-oriented classroom has useful daylight illuminance for 94.5% of the occupied hours of the year, which is larger than that of classrooms in other orientations. The west- and south-oriented classrooms have almost similar UDI, i.e. 84.7% and 85.3%, respectively. Finally, the east-orientated classroom has the lowest UDI, i.e. 72.1%. This comes in line with the $UDI_{>2000}$ and $DAmax_{>3000}$ which are indicators for over-lit spaces. The north-oriented classroom has lower potential for oversupply of daylight, i.e. 4.5% of the occupied hours of the year display a UDI value of more than 2000 lux and only 25% of the space shows DAmax above 5% of the time. Conversely, for the east-oriented classroom, 27% of the occupied hours of the year exhibit daylighting above 2000 lux and 71% of the space reaches DAmax value for more than 5% of the time, which consequently leads to glare issues. An indication for over illuminance is also shown in the west-oriented classroom with daylighting above 2000 lux for 14.3% of the occupied hours of the year, while 59% of the space reaches DAmax value (>3000 lux) above 5% of the time. The west-oriented classroom shows possible glare issues half of the period compared to the east-oriented classroom. This relates to the fact that during the occupied hours of the year the sun faces only the clerestories of the west-oriented classroom. In terms of the south-oriented classroom, potential for glare was also observed, but for less time compared to the west-oriented classroom, i.e. 13.8%. Specifically, in the south-oriented classroom, 33% of the space reaches DAmax value (>3000 lux) above 5% of the time. The dynamic simulation results of the reference scenario are comprehensively presented in the Table below (Table 17.3).

Table 17.3. Dynamic simulation results of the reference scenario.

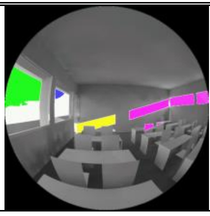
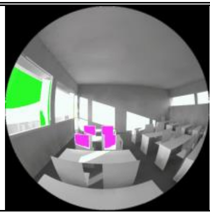
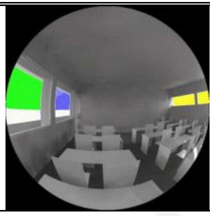
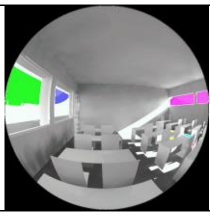
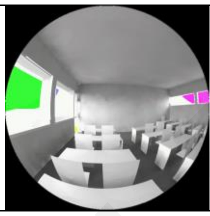
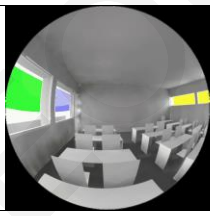
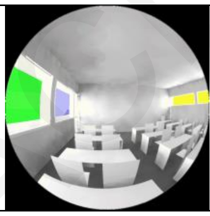
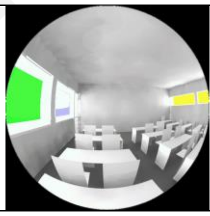
| Ref. Scenario | Daylight Autonomy (DA) | | Useful Daylight Illuminances (UDI) | | | | Max Daylight Autonomy | |
|---|---|---|---|---|---|---|---|---|
| | **Average DA (>300 lux)** | **DA range (min-max)** | **Average $UDI_{<100}$** | **Average $UDI_{100-2000}$** | **$UDI_{100-2000}$ range (min-max)** | **Average $UDI_{>2000}$** | **Average DAmax** | **% of space DAmax > 5% of time** |
| | **percentage [%] of the occupied hours of the year** | | | | | | | |
| **East** | 97.0 | 92 - 99 | 1 | 72.1 | 13 - 99 | 27.0 | 17.4 | 71 |
| **West** | 95.7 | 87 - 99 | 1 | 84.7 | 53 - 99 | 14.3 | 8.9 | 59 |
| **South** | 95.3 | 80 - 99 | 1 | 85.3 | 35 - 99 | 13.8 | 6.3 | 33 |
| **North** | 94.1 | 86 - 98 | 1 | 94.5 | 72 - 99 | 4.5 | 2.6 | 25 |

### *17.3.2. Analysis of Glare Metric*

In order to evaluate the discomfort glare conditions of the working space, an analysis with the Hdrscope software was performed. The simulation analysis was conducted during three representative periods of the year, i.e. on the 21st of December, the 21st of March and the 21st of June, at 08.00 a.m., 10.00 a.m. and 12.00 noon. The sky condition was set as intermediate for the winter solstice and equinox and as sunny for the summer solstice. The positions of the cameras were set in three points of the classroom as shown in Figure 17.3. For the illustration of results, the position next to large windows (C1) was selected as it showed increased glare issues compared to other positions. The illustration of results is presented on a comparative basis in Tables 17.4 – 17.6. It should be noted that according to the software, glare issues might be underestimated in cases of low brightness scenes and thus results are not given. Glare sources are indicated in the scenes by coloured surfaces, although colours are of no significance [469]. Disability glare is qualitatively detected where light causing a haze of veiling luminance decreases contrast and reduces visibility.

Extensive discomfort glare issues are observed during morning time, at 08:00 a.m., almost in all orientations throughout the entire the year. In the east-oriented classroom, during winter solstice, the glare index reaches the intolerable degree of glare sensation, i.e. 0.54, due to low solar altitude. Although the discomfort glare probability (DGP) is lower than 0.30 during spring equinox and summer solstice in the east-oriented classroom, disability glare is detected throughout the entire year at 08:00 a.m. In the west-oriented classroom, the discomfort glare probability (DGP) index is not available for winter solstice and spring equinox, although disability glare is detected on the writing board area, as well as on the working surface of the students, throughout the year. High disability glare issues also occur in the south-oriented classroom, especially in the front part, mostly during the winter period. In the north orientation, glare is limited and appears at the back of the classroom due to the fact that lighting enters the space through the southern clerestories (Table 17.4).

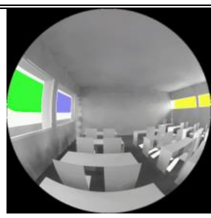
Table 17.4. Illustration of natural lighting results of classrooms in all orientations during winter solstice, equinox and summer solstice, at 08:00 a.m. Random colours highlight the detected glare sources.

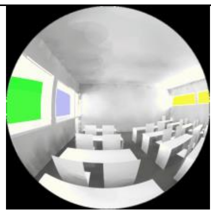
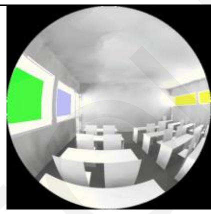
| | East | West | South | North |
|---|---|---|---|---|
| **08:00 a.m. December 21st Winter Solstice** |  |  |  |  |
| | 0.54 | - | - | - |
| **08:00 a.m. March 21st Spring Equinox** |  |  |  |  |
| | 0.24 | - | - | 0.21 |
| **08:00 a.m. June 21st Summer Solstice** |  |  |  |  |
| | 0.27 | 0.24 | 0.24 | 0.24 |

- No available results due to low brightness scene

At 10:00 a.m. the discomfort glare probability (DGP) is lower than 0.30 during all periods under study and in all orientations. Greater potential for disability glare is presented in the east-oriented and south-oriented classroom, throughout the entire year. During the winter period, disability glare appears on the students' desks and on the writing board, due to the low solar altitude. During the intermediate period, glare issues appear more rarely due to the shading caused by the overhang. Finally, during the summer period, disability glare issues appear to be even more intense due to the high lighting levels of the external environment (Table 17.5).

Table 17.5. Illustration of natural lighting results of classrooms in all orientations during the winter solstice, equinox and summer solstice, at 10:00 a.m. Random colours highlight the detected glare sources.

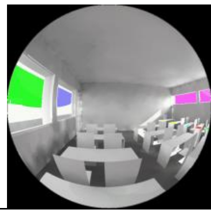
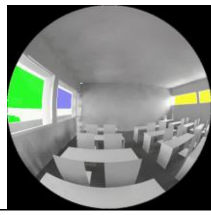
| | East | West | South | North |
|---|---|---|---|---|
| **10:00 a.m. December 21st Winter Solstice** |  |  |  |  |
| | 0.23 | - | 0.23 | 0.21 |

| | | | | |
|---|---|---|---|---|
| **10:00 a.m.<br>March 21st<br>Spring Equinox** |  |  |  |  |
| | 0.24 | - | 0.21 | 0.22 |
| **10:00 a.m.<br>June 21st<br>Summer Solstice** |  |  |  |  |
| | 0.24 | 0.23 | 0.23 | 0.23 |

- No available results due to low brightness scene

At 12:00 noon, the discomfort glare probability (DGP) is lower than 0.30 during all periods under study and in all orientations. In terms of disability glare, extensive issues are predicted in all orientations at 12:00 noon during the summer period. Comparing the classrooms with different orientations, the south-oriented classroom shows higher glare issues than others throughout the entire year, despite the existence of the southern overhang. This is due to the position of the sun at noon facing directly the south (Table 16.6).

Table 17.6. Illustration of natural lighting results of classrooms in all orientations during the winter solstice, equinox and summer solstice, at 12:00 p.m. Random colours highlight the detected glare sources.

| | **East** | **West** | **South** | **North** |
|---|---|---|---|---|
| **12:00 noon<br>December 21st<br>Winter Solstice** |  |  |  |  |
| | 0.22 | 0.20 | 0.24 | 0.21 |
| **12:00 noon<br>March 21st<br>Spring Equinox** |  |  |  |  |
| | 0.22 | 0.20 | 0.22 | 0.20 |
| **12:00 noon<br>June 21st<br>Summer Solstice** |  |  |  |  |
| | 0.24 | 0.24 | 0.25 | 0.24 |

- No available results due to low brightness scene

## 17.4. Proposed measures for visual comfort improvements

The static and dynamic simulations, as well as the glare analysis performed in the current study, allowed for the evaluation of the natural lighting performance and visual comfort in the typical classroom of educational buildings in Cyprus. Based on the results drawn from the study, the classrooms in all orientations exhibit sufficient lighting levels. However, high lighting contrast and bright visible light source in the field of view cause glare issues in classrooms with specific orientations. The above conclusions are also confirmed by the results of the field study performed through a questionnaire-based survey. Artificial lighting is used during the entire year during all working hours of the day because curtains are kept closed to control glare issues which, in turn, increase the energy consumption. Based on the above, the need for implementation of a series of measures to improve both discomfort and disability glare issues in classrooms, as well as to reduce the use of artificial lighting, becomes evident. More specifically, the glare analysis through the Evalglare software is in line with the results extracted from the Daysim software indicating glare issues mostly in east- and west-oriented classrooms followed by south-oriented classrooms.

Potential improvements are proposed depending on the different orientations of the classrooms. Based on relevant literature review, louvers and blinds seem to be feasible lighting regulating systems [481], [482]. A feasible solution for east and west-oriented classrooms that may contribute to the decrease of glare issues without the reduction of the lighting levels could be vertical stable louvers of width to free space ratio equal to 1. It is noted that, for the particular cases under investigation, stable louvers are preferred due to their low installation and maintenance costs, as well as due to lack of operating costs compared to the movable systems (Figure 17.4). The first floor was selected for simulation purposes where he louvres were placed at the edge of the semi-open corridor of the first floor and in contact with the openings of the ground floor. The width of louvers was set at 0.30 m since the rotation angle was set vertical to the windows. The reflectance of the louver components was set at 0.5.

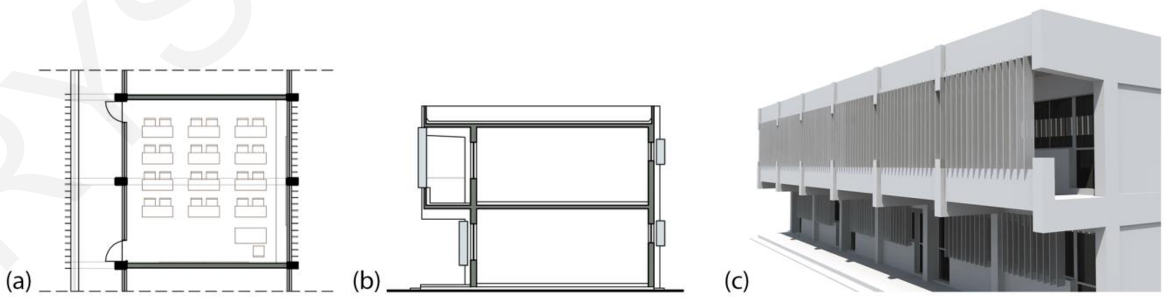



Figure 17.4. (a) First floor plan and (b) section of a typical classroom with the application of the vertical stable louvers for the reduction of glare issues in east- and west-oriented classrooms. (c) Photorealistic view of a linear disposition of classrooms with the proposed lighting and glare regulating system.

The use of suitable internal blinds in the form of movable semi-transparent fabric panels or rolls are examined with different lighting properties in terms of visible light transmittance i.e. 10%, 30% and

50%; while, colour reflectance was set at 0.75. The above-described systems are used both alone and in combination with each other, aiming at improving visual comfort conditions in classrooms with different orientations. The proposed improvement strategies are summarized in Table 17.7.

Table 17.7. Proposed improvement scenarios and static simulation results.

| **Improvement Scenarios** | **Vertical Louvers** | | **Internal Blinds** | | | **Static simulation results** | |
|---|---|---|---|---|---|---|---|
| | **East** | **West** | **50%** | **30%** | **10%** | **Average DF [%]** | **% of space DF>2%** |
| **East-oriented Classroom** | | | | | | 2.8 | 83 |
| **E-1** | ■ | | | | | 2.6 | 81 |
| **E-2** | ■ | ■ | | | | 2.5 | 64 |
| **E-1a** | ■ | | ■ | | | 2.4 | 59 |
| **E-1b** | ■ | | | ■ | | 2.2 | 57 |
| **E-1c** | ■ | | | | ■ | 1.9 | 57 |
| **West-oriented Classroom** | | | | | | 3.0 | 86 |
| **W-1** | ■ | | | | | 2.9 | 80 |
| **W-2** | ■ | ■ | | | | 2.7 | 75 |
| **W-1a** | ■ | | ■ | | | 2.5 | 63 |
| **W-1b** | ■ | | | ■ | | 2.3 | 60 |
| **W-1c** | ■ | | | | ■ | 2.0 | 58 |
| **South-oriented Classroom** | | | | | | 3.0 | 86 |
| **S-a** | | | ■ | | | 2.5 | 63 |
| **S-b** | | | | ■ | | 2.3 | 58 |
| **S-c** | | | | | ■ | 2.0 | 58 |
| **North-oriented Classroom** | | | | | | 3.0 | 86 |
| **N-a** | | | ■ | | | 2.8 | 74 |
| **N-b** | | | | ■ | | 2.6 | 67 |
| **N-c** | | | | | ■ | 1.8 | 48 |

Results derived from the static and dynamic simulation, for each one of the proposed improvement scenarios in all orientations, are presented in Tables 17.7 and 17.8 respectively and are comparatively discussed below. Regarding scenario E-1, which involves applying louvers only on the east windows of the east-oriented classroom, the average daylight illuminance above 2000 lux reduced from 27% to 23.5% of the occupied hours of the year. In this scenario, the east-oriented classroom has daylight autonomy for 96.6% of the occupied hours of the year. Regarding scenario E-2, which involves applying louvers both on the eastern windows and western clerestories, the percentage of daylighting illuminance above 2000 lux, was only slightly reduced to 23.3%; therefore, it is not considered as a cost-effective solution. Regarding scenario W-1, which involves applying louvers on the eastern clerestories of the west-oriented classroom, the average daylight illuminance above 2000 lux reduced from 14.3% to 12.6% of the occupied hours of the year. In this scenario, the west-oriented classroom has daylight autonomy for 95.2% of the occupied hours of the year. Regarding scenario W-2, which involves applying louvers on both eastern clerestories and western windows, the percentage of daylighting illuminance above 2000 lux reduced slightly only to 12.4% (Table 17.8). Similar to scenario E-2, scenario W-2 is not considered as a cost-effective solution. The minimum differentiation compared to E-1 and W-1 scenarios, is due to the fact that western clerestories in the case of the east-oriented classroom and western windows in the case of the west-oriented classroom, receive natural lighting during afternoon hours which are not set as occupied hours. It is noted that more densely arranged louvers, or louvers with different rotation angle, have also been investigated. However, their application has been rejected since they drastically reduce lighting levels below the acceptable limits. Moreover, both E-1 and W-1 scenarios maintained the DF index above acceptable levels. As shown in Table 17.7, E-1 scenario achieves an average DF of 2.6% and the percentage of the space with DF above 2% is 81%; similarly, W-1 scenario achieves an average DF of 2.7% and the percentage of the space with DF above 2% is 80%.

In the south-oriented classroom, the existing overhang of 2.0 m in front of the large southern windows is considered as an appropriate shading device for the south orientation especially for summertime. Glare issues in the north-oriented classroom are limited and mostly attributed to southern clerestories. Due to the clerestories' small height of 0.60 m, the thickness of the structure itself creates an overhang with width to height ratio 1:2, hence, no additional fixed shading is examined.

Aiming at further improving the visual comfort conditions, the proposed scenarios involving the application of transparent blinds with different lighting properties were examined in classrooms of all orientations. In contrast to fixed shading devices, blinds provide flexibility, allowing the users to adjust and control lighting levels. For the needs of the current study, it is taken that blinds are applied throughout the entire year in order to include the sunny days. This however, affects negatively the lighting results of the classroom during overcast daysm i.e. a period when blinds are expected to be open. Despite this fact, all scenarios involving the application of transparent blinds maintained the average DF above or nearly within acceptable levels, as shown in Table 17.7. Moreover, as presented in Table 17.8, blinds with variant visible light transmittance, significantly reduced glare issues in all orientations. Blinds with 50% and 30% visible light transmittance, combined with the fixed shading device in the eastern windows and clerestories, reduced glare issues by about 20% and 25% respectively compared to the reference scenario. Blinds with 10% visible light transmittance in all orientations, in combination with the fixed shading device, reduced the glare problem by about 35% compared to the reference scenario. Specifically, in the east-oriented classroom, the UDI>2000 lux decreased from 27% to 18.3%, in the west-oriented classroom from 14.3% to 9.7%, in the south-oriented classroom from 13.8% to 9.5% and in the north-oriented from 4.5% to 2.4% of the occupied hours of the year.

Table 17.8. Dynamic simulation results of proposed improvement scenarios.

| Proposed Scenarios | Daylight Autonomy (DA) | | Useful Daylight Illuminances (UDI) | | | | Max Daylight Autonomy | |
|---|---|---|---|---|---|---|---|---|
| | Average DA (>300 lux) | DA range (min-max) | Average $UDI_{<100}$ | Average $UDI_{100-2000}$ | $UDI_{100-2000}$ range (min-max) | Average $UDI_{>2000}$ | Average DAmax | % of space DAmax > 5% of time |
| | percentage [%] of the occupied hours of the year | | | | | | | |
| **East-oriented Classroom** | | | | | | | | |
| **E-Ref.** | 97.0 | 92 - 99 | 1.0 | 72.1 | 13 - 99 | 27.0 | 17.4 | 71 |
| **E-1** | 96.6 | 86 - 99 | 1.0 | 75.4 | 20 - 99 | 23.5 | 15.5 | 68 |
| **E-2** | 96.1 | 46 - 99 | 1.1 | 75.7 | 14 - 99 | 23.3 | 15.4 | 68 |
| **E-1a** | 95.0 | 44 - 99 | 1.2 | 76.6 | 13 - 99 | 22.2 | 14.7 | 67 |
| **E-1b** | 85.5 | 6 - 99 | 1.9 | 77.0 | 15 - 99 | 21.1 | 13.7 | 61 |
| **E-1c** | 65.0 | 0 - 99 | 32.4 | 49.3 | 0 - 99 | 18.3 | 11.8 | 48 |
| **West-oriented Classroom** | | | | | | | | |
| **W-Ref.** | 95.7 | 87 - 99 | 1.0 | 84.7 | 53 - 99 | 14.3 | 8.9 | 59 |
| **W-1** | 95.2 | 80 - 99 | 1.0 | 86.4 | 52 - 99 | 12.6 | 8.1 | 56 |
| **W-2** | 94.8 | 75 - 99 | 1.1 | 86.5 | 51 - 99 | 12.4 | 8.0 | 55 |
| **W-1a** | 92.3 | 39 - 99 | 1.5 | 87.2 | 54 - 99 | 11.3 | 7.0 | 51 |
| **W-1b** | 85.8 | 6 - 99 | 2.5 | 86.9 | 54 - 99 | 10.6 | 6.4 | 44 |
| **W-1c** | 64.1 | 0 - 99 | 30.2 | 60.1 | 1 - 100 | 9.7 | 6.0 | 40 |
| **South-oriented Classroom** | | | | | | | | |
| **S-Ref.** | 95.3 | 80 - 99 | 1.0 | 85.3 | 35 - 99 | 13.8 | 6.3 | 33 |
| **S-a** | 91.7 | 23 - 99 | 1.4 | 88.0 | 35 - 99 | 10.6 | 5.1 | 29 |
| **S-b** | 85.5 | 0 - 99 | 3.4 | 86.5 | 35 - 99 | 10.1 | 4.7 | 26 |
| **S-c** | 63.6 | 0 - 99 | 33.3 | 57.3 | 0 - 99 | 9.5 | 4.3 | 22 |
| **North-oriented Classroom** | | | | | | | | |
| **N-Ref.** | 94.1 | 86 - 98 | 1.0 | 94.5 | 72 - 99 | 4.5 | 2.6 | 25 |
| **N-a** | 91.8 | 1 - 99 | 1.4 | 92.2 | 61 - 99 | 6.5 | 2.5 | 23 |
| **N-b** | 83.3 | 0 - 99 | 2.3 | 91.2 | 1 - 17 | 6.5 | 2.5 | 22 |
| **N-c** | 62.2 | 0 - 97 | 22.2 | 75.3 | 0 - 99 | 2.4 | 1.9 | 18 |

The glare simulation analysis of classrooms for all potential improvement scenarios was performed using the Evalglare tool. Indicative fisheye images, for E-1b, W-1b, S-b and N-b scenarios, i.e. application of vertical louvers in the eastern windows and clerestories of east- and west-oriented classrooms, combined with the application of blinds with 30% visible light transmittances in windows and clerestories of classrooms in all orientations, are presented below. As shown in Table 17.9, the simulations which refer to the 21st of June at 12:00 at noon under a clear sky condition, i.e. a period with intensive glare issues, reveal significant reduction of disability glare issues in all orientations and thus reduction of the building energy demand attributed to artificial lighting as a result of the non-use of internal curtains.

Table 17.9 Illustration of natural lighting results of classrooms with potential improvement scenarios in all orientations during and summer solstice, at 12:00 noon after.

| | **East** | **West** | **South** | **North** |
|---|---|---|---|---|
| | **Scenario E-1b** | **Scenario W-1b** | **Scenario S-b** | **Scenario N-b** |
| **12:00 noon June 21$^{st}$ Summer Solstice** |  |  |  |  |
| | - | - | - | - |

- No available results due to low brightness scene

## 17.5. Synopsis and Discussion

The current study addressed the natural lighting performance and visual comfort of educational architecture through the investigation of typical school premises in Cyprus. The research highlights that typical teaching spaces in Cyprus ensure sufficient natural lighting levels throughout the entire year in all orientations, as they meet DF above 2% for more than 83% of the space and daylight autonomy (300 lux) for more than 94% of the occupied time. This is due to high opening to floor ratio i.e. 35% and to the existence of bilateral openings on the two long facades of classrooms. The results are in line with relevant research studies that indicate high daylighting in educational buildings in Greece [311], [312]. The daylight uniformity of classrooms in all different orientations can be described as acceptable according to Building Bulletin 90 [302]; whereas, according to BREEAM [300], east- and north-oriented classrooms do not meet the uniformity ratio of at least 0.4. Different intensity and distribution of natural lighting is demonstrated in classrooms with different orientations. The incidence of direct sunlight causes glare due to excessive contrasts in the visual field of students. Moreover, indirect glare is caused by reflections on the working surfaces and on the writing boards of the classroom. This is also in line with relevant studies that indicate glare issues in educational buildings in Italy, as well as in Greece [309]–[312]. More specifically, intense glare is observed in the west- and east-oriented classrooms, appearing mainly on the working surfaces. This is the result of inappropriate shading devices on the eastern windows and clerestories. Insufficient lighting distribution and glare issues, as a result of the use of non-suitable shading devices, are also reported in the research studies performed by Axarli and Meresi [311], [312]. In the south-oriented classroom, limited glare issues are observed despite the existence of an appropriate shading device i.e. overhang of 2 m, while north-oriented classrooms demonstrate minimal glare issues, with this happening only during midday hours of the summer period. It is noted that the north-oriented classroom (i.e. classrooms with their large windows towards north and clerestories without shading system towards south) shows optimum performance, in terms of quantity of light and avoidance of glare, as light enters indirectly into the classroom. Consequently, north-oriented classrooms are quite suitable to be used as painting and drawing workshops or libraries as they are spaces that may satisfy high demands of constant daylight. However, north-oriented classrooms do not offer direct solar gains, i.e. passive heating strategies during the cold winter and intermediate periods. The above results, drawn from the static and dynamic lighting simulations as well as from glare analysis, are also confirmed by the results of the field study demonstrating satisfactory natural lighting levels. In terms of glare, the majority of students claim for glare issues. Based on the results of the questionnaire-based survey, artificial lighting is used throughout the year, at all working hours of the day, indicating that black-out curtains are kept closed, most probably, to control glare and over-lighting problems. This leads to reduction of the illuminance levels and simultaneous reduction of direct solar gains. These results are also reported in the research study performed by Theodosiou and Ordoumpozanis [313].

The study proposes improvements depending on the different orientations of the classroom in order to deal with glare problems, maintain acceptable lighting levels and eliminate energy consumption of artificial lighting. For east- and west-oriented classrooms, the study proposes fixed vertical louvers with width to free space ratio equal to 1, which based on relevant literature review, is a feasible solution for the specific orientation [481]. However, it should be noted that fixed louvers cannot comply with the lighting requirements of each time of the day. Therefore, an internal movable shading device is also deemed necessary [482]. The use of suitable internal blinds in the form of movable semi-transparent fabric panels or rolls, ensures the reduction of glare issues, without significant reduction of natural lighting levels. Moreover, these blinds allow insolation from the sun and the visual connection of the interior of the classroom to the outside environment. For south-oriented classrooms, only movable internal blinds are suggested since the existing overhang of 2.00 m is considered to be an appropriate shading device for southern openings. Finally, the north-oriented classroom provides constant daylight and has negligible glare issues; thus, only internal movable blinds are proposed. It is worth mentioning that blinds, with an appropriate automated control system, seem to be a more appropriate solution compared to manually controlled blinds by occupants who often neglect to adjust and readjust the blinds according to the external environment conditions. This is also in line with related studies which demonstrate that the controlled operation of the movable shading system contributes not only to the improvement of visual comfort conditions, but also to the thermal performance of the building offering appropriate shading during the hot summer period and insolation during the cold winter period [483], [484]. Furthermore, active solar systems could be integrated into the external lighting regulating system, allowing solar energy production [495], [499]. The integration will contribute positively to the overall energy balance of the educational building, while energy and environmental awareness will be promoted through the educational building's users.

# Chapter 18. Conclusions

## 18.1. Introduction

The indoor environmental quality of school buildings, particularly indoor thermal comfort, air quality and visual comfort in classrooms, have become of interest worldwide, predominantly because of their influence of students' health, learning performance and productivity. Growing concerns with building energy efficiency reinforce the subject's importance and value. Furthermore, with the recent global spread of the Covid-19 virus, educational buildings have become central to both global and local efforts of controlling the pandemic, making the provision of fresh air throughout the entire academic year not only an ideal situation to achieve in the future, but a crucial and vital necessity.

The broader scope of the present thesis was to develop a multi-criteria evaluation in order to allow the comparison between the results and validate the outputs as much as possible in order to take correct decisions for the upgrade and decarbonisation of existing educational building stock; one that takes into account both energy upgrading and adaptation to climate change. Educational buildings are particularly demanding buildings, both in terms of comfort conditions and at the same time, they are have high energy demands.

For the investigation of the thermal and visual comfort and air quality, different methodological approaches, adopted from different research fields, were used. Specifically, the theoretical background of the research was established through a literature review, highlighting elements related to the knowledge gap regarding thermal and visual comfort and air quality evaluation in free-running indoor environments with students as the long-term occupants. The review of the studies analyzing similar type buildings at the same educational level and within specific climate zones reveal that there has been a wide disparity in the obtained thermal neutrality. This finding underlined the need for more micro-level thermal comfort studies covering different cultural and social backgrounds that also reflects the experience and expectations of students. Moreover, the literature review highlighted the importance of conducting a subjective surveys, for the validation of results as the evaluation using comfort standards sometimes underestimates or overestimates the actual sensation. The outcomes from previous air quality studies reinforced the need for further research in the field; as enlarging the sample size and seasonal field investigations throughout the school year enhances the quality of the data and develops an understanding of students' air quality perception. Although visual comfort in educational buildings is a multifaceted research field of high interest, the existing literature is rather limited for educational buildings, and in particular for educational buildings in the Mediterranean, and specially in Cyprus.

The literature review demonstrated that climate change surveys in educational premises have been limited. Understanding the impact of climate change on buildings enhances the development of appropriate measures to mitigate the effect of climate change under the current and future climatic conditions. The outcomes from previous studies reinforce the need for further research in the field, particularly in naturally-ventilated secondary schools in the east-Mediterranean region. This research has conducted an extensive study to contribute to the understanding of the impact of climate change based on the current and future climate change scenarios on educational buildings in Cyprus, with the aim of improving the performance of classrooms contributing to energy efficiency policies and decision-making regarding retrofit interventions.

In order to perform this, the representative types of educational buildings in Cyprus were investigated and the evaluation of the typical school building was carried out, in terms of the organization, operation and the architectural expression of the structured and outdoor space. This was supplemented with the assessment of the construction and environmental approach of the school complex.

The above investigation provided the appropriate study sample for which a quantitative recording, analysis and documentation of parameters that affect the comfort conditions was carried out together with the appraisal and prediction of the energy performance of school buildings both under the current and future climatic conditions. This was done using environmental parameter recording equipment, calculation investigation and software simulation of comfort parameters and the appraisal of the energy behaviour of the building envelope was performed through computer software. In addition, through on-site observation and questionnaires (field research), building occupants' views on comfort conditions were recorded aiming to record the actual perception of users.

An investigation of comfort conditions and energy performance was carried out in classrooms in their current state and after proposals at architectural, construction and operational level.

The above contributed to the evaluation of the basic parameters that determine the comfort inside the classrooms and their energy behaviour. The investigation of the existing design and constructional nature of the typical school building in terms of the envelope and the surrounding area, led to the formulation of proposals for upgrading the educational building stock and the drafting of regulatory level guidelines to improve the comfort and energy behaviour conditions presented below.

This chapter reiterates the central aim of the thesis and outlines how the basic research questions were answered. The discussions and conclusions related to the thesis findings are explained and interpreted in light of the research as a whole. Furthermore, this final chapter considers the limitations and implications for future research and identifies suggestions for how building design practice can improve comfort and energy performance in classrooms.

## 18.2. Synopsis of the main results of the thesis

### *18.2.1. Conclusions regarding thermal comfort*

This thesis sought to investigate [through physical monitoring, a questionnaire-based survey and dynamic simulation] the indoor thermal comfort conditions of a typical classroom at a secondary school in Cyprus.

A comparative analysis conducted for the needs of the present study has enabled a scientific, qualitative and quantitative, experimental in-situ assessment that provides valuable data in the area of thermal comfort. The key findings of the current study are as presented below:

- South-oriented classrooms performed better during the winter period but worst during the summer period compared to classrooms with other orientations.
- During the summer period, the findings showed that occupants suffer from summertime temperatures. The most usual ventilation strategy of single-sided ventilation failed to maintain thermal comfort conditions most of the time.
- During the summer period, the environmental climatic conditions of the Mediterranean region, featuring a high diurnal fluctuation, allow the exploitation of natural ventilation strategies for cooling purposes.
- During the winter period, the findings showed that classrooms remain within the comfort zone only during the time that they are supported by technical heating. During the weekends, i.e. periods which are unoccupied and non-technically supported, classrooms exhibited temperatures below the lower acceptability limit of the thermal comfort zone.
- Statistical analysis demonstrated correlations between the mean temperature of classrooms and the outdoor temperature ($p<0.05$).
- The results of qualitative survey demonstrate that the majority of students feel *neither too cold nor too hot* during winter and summer. Despite the fact that classrooms present lower temperatures than those calculated by the adaptive comfort standards during winter, the majority of students show high tolerance and feel comfortable. On the other hand, it is noteworthy that although temperatures are within the comfort zone during the summer period under study, students prefer an environment that is a bit cooler with a slightly higher air movement. This means that students are more sensitive to higher temperatures.
- The study helps policy-makers to understand the possible consequences of climate change using dynamic simulation in order to enhance decision-making regarding climate change policies.
- The study demonstrates that, most educational buildings in Cyprus cannot perform in a thermally-comfortable manner, neither in the present nor in future climatic conditions, indicating the urgent need to take action.
- A linear relationship is established between degree hours and mean outdoor air temperature, both in winter and summer.
- The rising temperature in the future will most probably lead to the reduction of total energy needs as heating demand is predominant in educational buildings and specifically by 15% in

2050 (from 3278.3 degree hours to 2793.5 in the first floor and from 3517.9 degree hours to 2921.6 in the ground floor) and by 27-29% in 2090 (from 3278.3 degree hours to 2400.9 in the first floor and from 3517.9 degree hours to 2485.2 in the ground floor), whereas cooling needs will increase by 50-80% in 2050 (from 3187.6 degree hours to 2658.1 in the first floor and from 3487.1 degree hours to 2921.6 in the ground floor),and subsequently by a staggering 135-213% in 2090 (from 3187.6 degree hours to 2187.5 in the first floor and from 3487.1 degree hours to 2388.6 in the ground floor) which will obviously further exacerbate thermal comfort.

The experimental results presented in this study assess the effects of climatic variables on the indoor thermal conditions of schools in hot and dry environmental conditions. The study shows that adaptation measures are required in order to reach thermal comfort and air quality inside buildings, with favourable results on the well-being and the efficiency of people who occupy school premises.

### *18.2.2. Conclusions regarding retrofitting measures for the improvement of thermal comfort*

The climate is changing and there are clear indications that temperatures will continue to rise. The existing educational building stock, which mostly relies on natural ventilation during the cooling period, is expected to have significant impact on the users' thermal comfort, well-being and productivity.

This study aims to support enhanced decision-making about climate change and help policy-makers to understand its possible consequences, together with suggesting available adaptation options and the benefits of slowing the rate of climate change. Specifically, this thesis investigates the potential of adopting passive-building-related measures with a view to address thermal discomfort in educational buildings of Cyprus. For this purpose, the research aimed to evaluate the effectiveness of different retrofitting measures and their implications on the thermal comfort and the energy performance of educational premises under current and future climatic scenarios. Based on a calibrated dynamic thermal simulation model, optimization measures in terms of geometry, construction and operation were examined as to their effectiveness in minimizing heating demand and overheating conditions in the summer period. Additionally, the potential of natural ventilation in reducing energy needs and improving thermal comfort and air quality was extensively examined both using on-site experimental procedure as well as dynamic simulation

The key findings of the field survey study are as presented below:

- Different ventilation strategies observed during the field survey show that night ventilation has the highest cooling performance efficiency and thus less cooling degree-hours and lower peak temperatures during the day.
- Night ventilation alone performs better than night and day ventilation in terms of peak temperatures. However, ventilation during day-time maintains indoor air quality and increases wind speed, which in turn makes occupants feel more comfortable.

- The study confirms that cross-ventilation strategies using both the main openings and the clerestories also aid the removal of hot air, therefore playing a significant role in improving the indoor thermal comfort conditions.

This is also confirmed by the study regarding the potential of natural ventilation in the reduction of overheating risk using dynamic simulation. The key findings of the simulation survey study regarding natural ventilation impacts are as presented below:

- The night ventilation strategy has a positive contribution to the cooling effect of indoor spaces during the hot summer period.
- In the TMY, reducing daytime ventilation while using night ventilation produces better thermal performance, meeting the overheating criteria.
- Classrooms in the future climatic conditions of the 2050s and 2090s are predicted to suffer from overheating, specifically for more than half of the occupied period in 2050 and more than 70% of the time in 2090.
- In the future, daytime ventilation seems to be important for the removal of heat produced in the indoor environment from internal sources and solar heat gains.
- Ventilation alone however, is unable to cope with overheating predictions by solely relying on the current passive cooling strategies, as it can only achieve a reduction of hours where operative temperature exceeds CIBSE limits of 28-35% by 2050s and of 9-11% by 2090s.
- The study indicates that other passive strategies should be considered.
- Classrooms in all orientations in the future will require active systems to cope with overheating. Regulations and guidelines need to effectively address this scenario and promote solutions to minimise its cooling loads. The development of a methodological tool for the evaluation of the resilience of existing educational buildings can be of interest to architects, city planners and retrofit decision-making agents, as well as emergency response planners.

As a consequence of the abovementioned reasons, mild retrofitting measures were investigated, with a series of simulation runs, in order to identify their potential through software simulation. The key findings of the simulation survey study regarding proposed retrofitting measures are as presented below:

- The study revealed that individual improvements cannot prevent the need for active cooling systems.

- Both natural ventilation and insulation of the roof are considered very important in improving of thermal comfort as their combination can reduce cooling degree hours by 96.8%.
- Natural ventilation is predicted to become less effective in the future as demostrated, and consequently additional measures must be considered.
- Thermal insulation plays an important role both in the current and future climatic conditions in obstructing heat loss during winter and heat gains during the summer.
- In the current climatic conditions, the combination of passive measures (thermal insulation of building envelope, daytime and night-time ventilation and movable shading) can reduce heating degree hours by 27% with the potential of completely reducing cooling degree hours (100%), whilst by adding MVHR, the overall decrease reaches 51%.
- In the future, the combination of passive measures and the installation of MVHR reduces the total degree hours by 60% and 66% in 2050 and 2090 while they decrease cooling degree hours by 99.8% and 96.4% in 2050s and 2090s respectively.
- The overall performance of passive cooling techniques seems to be reduced in the future and most probably artificial cooling will be unavoidable in order to maintain indoor thermal comfort and regulate humidity levels.

Efforts to adapt to climate impacts are going to be crucial for governments aiming at reducing energy costs, achieving resilience and fulfilling their role in protecting building users and infrastructure. This need for adaptation goes beyond the countries with hot climate and it is becoming gradually more urgent in communities across the globe. For that reason, decision-makers must promote capacity building of agents to anticipate and effectively plan for climate change by addressing local institutional challenges. This will in turn enhance the ability of those agents to perform practical adaptation strategies, and support systems in order to maintain crucial services and improve community readiness for climate variability in general.

Specifically, the proposed improvements will also increase the environmental awareness of the population, as schools have the most potential among public building forms to stand out as 'beacons of change. Students can be active and informed participants in managing the building envelope of classrooms and they can learn how to support energy saving initiatives through responsible user behaviour. Moreover, the study is of wider interest as the results produced may address similar typologies of educational buildings. These forms involve linear disposition room arrangements in contact with semi-open corridors, as well as construction techniques which can be met in regions all over the world that share similar climatic conditions.

### *18.2.3. Conclusion regarding retrofitting measures for the improvement of energy performance and their cost effectiveness*

This thesis presents an approach to design and assess energy demand retrofitting scenarios in order to contribute to retrofitting decision-making regarding educational buildings in Cyprus based on the evaluation of their long-term cost-effectiveness. Based on the calibrated dynamic thermal simulation model, optimization measures in terms of geometry, construction and operation were examined as to their effectiveness in minimizing the life cycle cost by reducing the need for energy as much as possible. The approach combines energy demand modeling and retrofit option rankings with life-cycle cost anaylsis (LCCA). The key findings of the simulation survey study regarding proposed retrofitting measures are as presented below:

- Based on the energy ranking, the most effective strategy was the installation of mechanical ventilation with heat-recovery achieving a reduction of primary energy consumption by about 49% followed by the installation of insulation on the roof with a primary energy reduction of about 18% and the installation of insulation on the wall with a primary energy consumption reduction of about 9%.
- Based on the LCCA, the aforementioned strategies are considered as the most cost-effective solutions.
- Increasing ventilation rates up to 1000l/s during nighttime, replacement of windows with more efficient technological solutions and additional shading devices on the south-oriented classrooms have lower impact on the energy performance of the building.
- Combined retrofit scenarios concerned light, medium and advanced retrofitting based on the performance of individual scenarios with the light retrofitting characterized by relatively high impact on the energy demand and easy installation, while the advanced is characterized by all the possible retrofit options and greater difficulty in installation. Combinations achieved energy demand saving of 62-77% in the educational buildings based on the retrofitting scenario.
- The combination of 10cm of insulation on the roof and walls with MVHR was a medium retrofitting scenario and reduced the energy consumption by 69% with a small increase of global cost by 10% in a real interest rate.
- The alternative of installation of 15cm of insulation on the roof instead of 10cm is also considered as a cost-effective strategy as the difference in the LCC is minor (only 1% compared to the aforementioned scenario) minimizing the energy demand by 70%.
- The retrofitting scenario that contained all the possible measures does not yield higher long-term economic profits as it can increase the LCC by about 84%.
- The sensitivity analysis regarding the increase of the discount rate to 3% has shown that the LCC of both the reference building and the retrofitting measures is decreased. The

retrofitting measures have a higher risk as the difference of LCCA in accordance to the reference building becomes higher.

- The sensitivity analysis regarding the increase in the rate of increase of the energy price has shown that the major impact on the LCC is given by the overall energy costs which have been increased and thus energy and environmental optimal solutions become also the most cost-optimal solutions.
- The sensitivity analysis of the decrease in the rate of increase of the energy price has shown again the major incidence on the LCC which is given by the overall energy costs which have been decreased and therefore the retrofitting scenarios have a higher difference compared to the reference building due to the initial investment cost.
- The sensitivity analysis on the school curriculum has shown that adaptation measures are considered even more effective when the curriculum is extended during the afternoon as the difference in the LCCA compared to the reference building is minimized. This is an important decision-making element that emphasizes the need for energy upgrades so that school buildings are suitable throughout the day.
- Specifically, the combination of 10cm of insulation on the roof and walls with MVHR reduced the primary energy request by 69% with a small increase of global cost by 4%, i.e. € 22,917 compared to the €22,063 of the reference building.
- Considering a further increase of energy price in the future, make the LCC of the aforementioned scenario under an extended curriculum almost the same with the reference building.
- The presented results underline that the selection of input parameters is highly influential.

The cost-optimal methodology may be a powerful tool of sustainability and helps the policy makers to identify and plan retrofit options on educational buildings in Cyprus. Recommendations provided a pilot step for future ministry-based analysis and on-site implementations. Moreover, the results of the present study can be used in educational buildings that share the same typological and climatic characteristics.

### *18.2.4. Conclusions regarding air quality*

This thesis investigated the indoor air quality conditions associated with thermal comfort in a typical classroom of a secondary school in Cyprus and explored the impact of natural ventilation on both thermal comfort and air quality using field measurements and questionnaires. More specifically, the study tries to trace the correlation between the daily activity of occupants and their window control pattern, investigating the conditions for appropriate manual airing. In this framework, various ventilation strategies and window opening patterns were examined in order to identify suitable practices to achieve optimum air quality without negatively affecting the thermal comfort of indoor spaces. It should be noted that, the balance between thermal comfort and air quality proves an essential parameter of indoor comfort especially during the winter period since the climatic conditions of the East-Mediterranean region require both heating and suitable ventilation rates for indoor air quality.

A comparative analysis of the findings of the present study has enabled a scientific quantitative assessment that provides valuable knowledge vis-à-vis indoor air quality, passive ventilation and thermal comfort. The key findings of this study are presented below:

- During the heating period, typical teaching spaces in Cyprus indicate high $CO_2$ concentrations demonstrating low levels of air quality within educational buildings. In the case of two consecutive occupied periods, $CO_2$ reaches values much higher levels than the limits defined by standards, demonstrating the need for frequent ventilation during the winter season.
- The application of natural ventilation strategies during every break-time has a beneficial impact on the reduction of $CO_2$ concentration without compromising thermal comfort. This ensures low levels of $CO_2$ and acceptable conditions during the following teaching period.
- Cross ventilation during break-time is an effective ventilation strategy in terms of $CO_2$ concentration reduction, compared to all other types of ventilation. Specifically, during a 20-minute break, the cross-ventilation strategy reduces $CO_2$ concentration from 3000ppm to 530ppm, i.e. by 82%, a significantly higher reduction percentage compared to any other ventilation strategy applied.
- A lower air change rate of continuous ventilation is necessary by operating the door or a single window during the occupied periods in order to keep the indoor air quality levels within the limits provided by international standards.
- A pattern-free investigation indicates that the window-opening behaviour of occupants is determined by poor air quality, i.e. high $CO_2$ concentration levels and odours. Moreover, it is highlighted that occupants' window control behaviour is also determined by outdoor temperature levels resulting in the windows remaining closed when outdoor temperatures are less than 15°C.
- During the summer period, students open the windows from the beginning of the day and keep them opened until the end of the teaching period in order to achieve both thermal comfort through air movement and air quality.
- Subjective questionnaires confirmed that students identify poor air quality with odours.

The results of the experimental study presented herein demonstrate the impact that environmental variables can have on the window operation by the occupants, while, at the same time, quantifying the positive contribution of different ventilation strategies for indoor air quality as well as their impact on indoor thermal conditions in educational buildings in hot and dry climatic conditions.

Finally, the study revealed the necessity for an appropriate manual airing routine for air quality and thermal comfort in the indoor built environment, with positive consequence on the well-being and the productivity of educational building occupants. The findings of the current study could be successfully employed beyond the geographical limits of Cyprus, since Eastern Mediterranean countries share similar climatic conditions and adopt similar building typologies in educational architecture.

### *18.2.5. Conclusions regarding visual comfort*

Natural lighting is an important factor in the design of education buildings as it increases productivity, promotes a healthy and pleasant environment while it reduces energy consumption that results from the use of artificial lighting. This study assesses the natural daylighting performance of the typical classroom in all orientations of educational buildings in Cyprus. The investigation of illuminance and visual comfort, by the simultaneous use of different methodological tools, form a holistic approach to the study which leads to a qualitative and systematic quantitative evaluation process that safeguards the reliability of the research results. Specifically, in-situ lighting measurements allowed the evaluation of natural daylighting performance of education buildings through primary data gathering. Moreover, it enabled the validation of the digital simulation model used for static, dynamic and glare analysis. Visual comfort was studied through the assessment of recognised metrics in terms of the amount of light, the uniformity of light, and the prediction of the risk of both discomfort and disability glare for occupants. Apart from the quantitative analysis, a field study through a questionnaire-based survey was used for the better understanding of lighting levels, lighting distribution, visual comfort conditions and use of artificial lighting in the indoor space of the classroom.

The evaluation of the daylighting performance of typical classrooms led to important and valuable findings in terms of the amount and uniformity of light and the prediction of glare. More specifically:

- Typical teaching spaces in Cyprus ensure sufficient natural lighting levels during all working hours of the day throughout the entire year in all orientations.
- The daylight uniformity of classrooms in all different orientations can be described as acceptable.
- Different intensity and distribution of natural lighting is demonstrated in classrooms with different orientations. The incidence of direct sunlight causes glare due to excessive contrasts in the visual field of students.
- Intense glare is observed in the west- and east-oriented classrooms, appearing mainly on the working surfaces. This is the result of inappropriate shading devices on the eastern windows and clerestories.
- Artificial lighting is used during the entire year during all working hours of the day, indicating that black-out curtains are kept closed, most probably, to control glare and over lighting problems.

Moreover, the research took a step towards defining design guidelines for the improvement of daylighting performance and thus, of human visual comfort. More specifically:

- The study proposed improvements depending on the different orientations of the classroom in order to deal with glare problems, maintain acceptable lighting levels as well as to reduce the use of artificial lighting.
- For east- and west-oriented classrooms, the study proposes fixed vertical louvers, which is proved to be a feasible solution for the specific orientations.
- The use of suitable internal blinds in the form of movable semi-transparent fabric panels or rolls is proposed in classrooms in all orientations, ensuring further improving of the visual comfort.

The current study investigates, in a systematic qualitative and quantitative manner, the optimization of natural lighting performance and visual comfort in the typical classroom of educational buildings in Cyprus. Apart from educational architecture in Cyprus, the research findings can be also applied in other areas of southern Europe with similar climatic characteristics and typologies in educational architecture. The multi-criteria evaluation methodology used introduces a holistic approach to the investigation of natural lighting performance and visual comfort and thus, contributes to knowledge in the relevant field.

## 18.3. Regulatory level guidelines of retrofit approaches for the improvement of comfort and energy performance of educational buildings

Proposals for the improvement of environmental comfort conditions are based on previous conclusions and existing literature, and refer to the improvement of the thermal, visual comfort, and air quality conditions of the classrooms of the typical school buildings. In addition, possibilities for improving the comfort conditions in school buildings are provided by interventions in the surrounding area. In addition to improving comfort conditions, the proposed measures and strategies ensure a significant reduction in the energy requirements of school buildings, with favourable environmental consequences.

### *18.3.1. Suggestions for improving thermal comfort conditions and energy performance*

Suggestions for improving thermal comfort conditions refer to improved thermal insulation of the building envelope, adequate sun protection through shading systems, natural and technical ventilation and the use of ceiling fans.

#### *18.3.1.1. Improvement of the insulation of thermal envelope through construction interventions*

The thermal insulation of the building envelope (wall, roof, floor, windows) protects the building envelope from the climatic conditions of the external environment, both during winter and summer period eliminating the rate of heat transfer through conduction, convection and radiation [384].

*18.3.1.1.1. New layer of exterior insulation on the walls*

To improve the energy performance and comfort conditions of the typical classroom, thermal insulation of the wall is suggested. The external installation of 100mm of rockwool insulation with λ=0,032 W/m.K is recommended. The external insulation is proposed in order to maintain the thermal mass inside the building through the brick wall including the structure from reinforced concrete. The thermal transmittance coefficient of the proposed external wall is 0.26 $W/m^2K$, therefore satisfying the requirements of the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020, which determines U ≤0,4 $W/m^2K$ as a maximum allowed value for the external walls which are part of the building envelope.

*18.3.1.1.2. New layer of exterior insulation on the roof*

To improve the energy performance and comfort conditions of the typical classroom, thermal insulation of the roof is suggested. The external installation of 150 mm of extruded polystyrene with λ=0,032 W/m K is recommended for a dry installation. In addition, pavement slabs will be installed. The use of pavement slabs protects the insulation from general damage and prevents it from flying or floating away due to wind or rain. The thermal transmittance coefficient of the proposed external roof is 0.19 $W/m^2K$, thereby satisfying the requirements of the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020, which determines U ≤0,4 $W/m^2K$ as a maximum allowed value for the external horizontal elements which are part of the building envelope such as the roof.

*18.3.1.1.3. New layer of insulation on the floor*

To improve the energy performance and comfort conditions of the typical classroom, thermal insulation of the floor is suggested. The installation of 50mm of extruded polystyrene with λ=0,032 W/mK is recommended for a dry installation. In addition, a screed with lightweight concrete and tiles are proposed. The U-value of the proposed construction is 0.5 $W/m^2K$ however, but in any case the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020, does not define a maximum allowed value for the floor in contact with the ground.

*18.3.1.1.4. Replacement of existing windows with relatively high-performance glazing systems and window frames*

To improve the energy performance and comfort conditions of the typical classroom, replacement of the existing single glazed windows with relatively high-performance glazing systems and window frames, is recommended. The proposed solution suggests double glazing 4mm thick with an air gap of 15mm with low heat emission coating (ε≤0.15) on one side (low-emissivity layer) and insulated frame. The thermal transmittance coefficient of the proposed window is 2.23 $W/m^2K$, satisfying the provision of the Ministerial Decree of Minimum Energy Efficiency of the Buildings retrofitted from 2020, which determines U ≤2.25 $W/m^2K$ as a maximum allowed value for the windows which are part of the building envelope.

*18.3.1.2. Shading system*

Adequate sun protection of glass surfaces is one of the most essential measures to ensure thermal comfort during the cooling period. According to the literature, as well as the results of the current thesis inappropriate shading devices can cause overheating during the warm season or increase the heating demand during the cold season. The most suitable sun protection of the southern openings is achieved by the use of horizontal overhang or blinds at the appropriate depth, while the eastern and western openings by the use of vertical blinds, awnings or grids [384], [388].

The combination of the abovementioned is the most appropriate sun protection for all orientations. The system could be fixed or movable external shading, movable internal shading or combination of external and internal. The most appropriate shading system appears to be a movable shading that traces the sun position and blocks the entrance of solar radiation into the classroom while allowing the sunlight when it is needed.

Specifically, the typical **south-oriented classroom**, which has the external 2 m-wide corridor on the first floor as an overhang, ensures direct solar gains during the heating period, partial solar gains during the intermediate period and almost full solar shading during the cooling period. Additional movable shading with louvers of 25 cm per 25 cm would be probably necessary in the future to minimize cooling loads.

**North-oriented classrooms** with large windows on the north side receive limited solar radiation during the entire year; however, the south clerestories require a horizontal overhang of 50cm in width.

**West and east-oriented classrooms** require vertical blinds. Adequate sun protection of the eastern and western main openings is achieved by placing vertical blinds 25 cm wide per 25 cm at the end of the overhang. The sun protection device ensures morning direct solar radiation throughout the year in the eastern openings and afternoon direct solar gains (after 15:30) in the western openings. The sun protection of the eastern and western clerestories is also achieved by placing vertical blinds 25 cm wide by 25 cm [38].

The installation of rotating vertical blinds, provides controlled sun protection against fixed devices for different periods of the year and hours of the day. It is noted that the requirement to handle sun protection devices is the subject of practical knowledge and participatory action in the context of an environmental education of students [38], [383], [388].

In addition, the installation of vertical blinds for sun protection in the eastern and western openings, provides advantages related to the creation of a shaded semi-open space for relaxation, the improvement of the distribution of light, the mitigation of glare, etc., which are mentioned in the following paragraphs.

Interior movable awnings (fabric perforated panels or shutters and Venetian blinds) are recommended in all orientations. Internal mobile sunshades, as opposed to fixed external ones, provide shading and adjustment of glare issues directly controlled by the user.

*18.3.1.3. Natural ventilation*

The characteristics of the Mediterranean climate make natural ventilation a particularly effective strategy for improving thermal comfort conditions, both during the summer and on the hottest days of the intervening seasons [196]–[200].

The open structure of the typical school building and especially the layout of the classrooms in the form of a linear arrangement, allows the bilateral existence of openings in the majority of the classrooms, ensuring cross ventilation of the functional spaces. Natural cross ventilation is achieved by simultaneously opening windows and clerestories on both sides of the classroom.

The positive contribution of **daily natural ventilation** is relatively limited, due to the high temperatures recorded. Based on the literature, ventilation is most appropriate where the air temperature and humidity fall within comfort limits. However, the movement of the air, as a basic parameter of thermal comfort, ensures a pleasant feeling due to the air currents that are created. In addition, it provides the necessary air exchange required for indoor air quality issues.

Considering that the environmental climatic conditions of the Mediterranean region are characterized by large daily fluctuations, **night ventilation** is deemed as an effective passive cooling strategy. Night ventilation ensures thermal discharge and cooling of the building envelope, thus reducing the cooling needs for the next day. This effect is enhanced by the thermally exposed mass of the building (reinforced concrete roofs and perforated ceramic brick walls), so that it is possible to store the “cold” during the night. For this reason, it is desirable to avoid the use of false ceiling systems and internal thermal insulation, where this is not necessary.

*18.3.1.4. Mild technical systems*

**Heat recovery ventilation** decreases the heat loss from ventilation dramatically during winter, and hence the hours of discomfort, as it provides controlled ventilation and ensures the required air exchange in order to maintain indoor air quality [390]. Specifically, the lowest ventilation rate of 8 l/s/person for schools is proposed to maintain indoor air quality. As for cooling, the alternator system can reverse the switching process (reversing the roles of the fans,) or cancel it completely so that the building is discharged at night from the heat stored during the day. The system operates always during the occupied period of 07:30- 13:35 throughout the school year, while during the summer period it is also on between 00:00-07:30 and 13:35-24:00 when outdoor air temperature is < 31°C and outdoor relative humidity is <70% to reduce the thermal loads of the building envelope.

*18.3.1.5. Ceiling fans*

Although elevated air speed resulting from the use of ceiling fans was not examined in the current thesis, their contribution is well-established in European Standards and well-acknowledged in the Mediterranean climate. The installation and use of **ceiling fans** in indoor spaces can improve thermal comfort conditions. The heat dissipation from the people in the spaces due to the movement of air from the operation of the ceiling fan, ensures an increase of the thermal comfort limit by 3 °C for an air speed of 0.9 m/s [87]. In this way, the feeling of thermal comfort is ensured at a significantly higher temperature. In addition, during the winter it can work in the opposite direction and transfer the warm air that is in the high points of the space down.

## *18.3.2. Suggestions for improving air quality and energy performance*

### *18.3.2.1. Natural ventilation*

The effects of indoor air quality on health, productivity and user availability demonstrate the need to ensure adequate air quality inside school buildings**.** The achievement of air quality in some cases, such as during the winter period, come in conflict with the achievement of thermal comfort. The main findings of the thesis show that **systematic natural ventilation of classrooms** during teaching periods as well as during breaks and after the departure of students is a satisfactory ventilation solution in terms of air pollution which is a result of human presence, without compromising the thermal comfort. Specifically, a lower air change rate of continuous ventilation by operating the door or a single window during the occupied periods is necessary in order to keep the indoor air quality levels within the lower limits provided by international standards and not affect the thermal comfort.

### *18.3.2.2. Heat recovery ventilation system*

The installation of **heat recovery ventilation systems** in classrooms provides controlled ventilation ensuring the required air changes per hour since it performs heat and moisture treatment before the fresh air enters the room [392]. It is especially recommended during the winter months, a period during which the level of air quality inside the classrooms deteriorates, given that the openings are kept closed in order to reduce heat loss through ventilation. Specifically, the lowest ventilation rate of 8 l/s/person for schools is proposed to maintain indoor air quality. The system operates always during the occupied period of 07:30- 13:35 throughout the school year, while during the summer period it is also on between 00:00-07:30 and 13:35-24:00 when outdoor air temperature is < 31°C and outdoor relative humidity is <70% to reduce the thermal loads of the building envelope. The use of pollution detection sensors ensures the safety and health of users.

## *18.3.3. Suggestions for improving visual comfort and energy performance*

Typical teaching spaces in Cyprus ensure sufficient natural lighting levels during all working hours of the day throughout the entire year in all orientations. The daylight uniformity of classrooms in all different orientations can be described as acceptable. Different intensity and distribution of natural lighting is demonstrated in classrooms with different orientations. The incidence of direct sunlight causes glare due to excessive contrasts in the visual field of students especially in the east and west classrooms.

Proposed measures to improve glare issues should be examined in correlation with solar gains for thermal comfort. The proposed systems below can be at the same time suitable sun protection devices as well as heat and ventilation regulators, as they have the appropriate geometric characteristics, as mentioned in previous paragraphs.

For **east and west-oriented classrooms**, a satisfactory solution is offered by **external vertical movable blinds**, rotating **on a vertical axis, or fixed**, meaning that internal movable shading is provided.

For **south-oriented classrooms**, due to the existing overhang in front of large windows of the typical classroom, light shelves are not deemed as a feasible solution for the improvement of visual comfort in the spaces under study.

The **north-oriented classrooms** have uniform lighting levels and do not require reflective lighting shelves or other devices.

The use of **semi-transparent blinds** in the form of movable fabric panels or roller shutters ensures further reduction of glare, without significant reduction of solar gains and without the visual exclusion of the interior of the classroom from the outside environment. The internal **horizontal movable blinds** (venetian blinds) also provide effective treatment of glare. Internal movable shading is recommended in all orientations, as it provides additional controlled shading and adjustment of glare issues.

To improve the distribution of natural light, it is recommended that the **colors** of the interior surfaces of the classrooms be light (white or off-white), ensuring uniform diffusion of light.

### *18.3.4. Synopsis*

The proposals for improving the environmental comfort conditions mentioned in the previous paragraphs can contribute significant benefits to improving the overall comfort conditions of existing educational buildings. They refer to the improvement of the thermal comfort, visual comfort and air quality conditions of the typical classrooms.

In addition to improving the comfort conditions and quality of life of users, the proposed measures and strategic actions refer to improving the energy behaviour of the school building, ensuring a significant reduction of energy requirements, with favourable environmental consequences.

## 18.4. Limitation of the research

The simultaneous examination of the comfort parameters and the investigation of the energy efficiency of the typical school building of Cyprus, was the main research intention of the present thesis. To ensure the completeness of the research process, methodological approaches from different research fields were used. During the thesis process, there was an effort to identify all the important factors that make the results as accurate and real as possible. Nevertheless, the findings of this study have to be seen in light of some limitations which some of them can be used as a potential direction for further research.

The first limitation is related to the examination of thermal comfort in educational buildings and the climatic zone that this thesis focuses on. The present study focused on the climatic zone 2 which is the lowland area; however, there are three other climatic zones in Cyprus. The justification of this shortcoming is based on the literature that stated that climatic zones 1,2 and 3 require the same duration for heating and cooling with slight differences on degree hours, therefore a generalization of conclusions was allowed. Moreover, the Ministry of Energy, Trade and Industry does not differentiate the Minimum Energy requirements for the different climatic zones.

The second limitation is also related to the examination of thermal comfort in educational buildings and specifically to the assessment of thermal comfort on-site and the methodological approach used. Although adaptive comfort standards presuppose that the buildings will not be technically supported by systems, educational buildings in Cyprus provide heating during winter affecting the thermal performance of classrooms. To minimize the negative effect of this limitation, an additional analysis has been made during weekends without the operation of any heating system without the impact of the presence of occupants however. Additionally, the variation in the occupancy levels of classrooms, and the lack of uninterrupted occupancy due to the fact that students move to other laboratory or physical education classrooms during the day, may influence the recorded indoor condition data. Finally, the subjective questionnaires were filled by responders on selected days of each season. Therefore, the recording of data during different days and periods of the year, with more variations in temperatures will allow a more detailed investigation of students' thermal sensation.

The third limitation concerns the evaluation of thermal and energy performance of educational building under the future climatic conditions. The choice of the climatic scenario A1B was based on the intermediate case, which lies in the middle of the 'business as usual' scenario and the 'united sustainable planet' extremes. However, there are many other projections for the future that could affect the evaluation of the thermal and energy performance of educational buildings both of the existing state and retrofit interventions.

The fourth limitation concerns the evaluation of adaptation measures for the improvement of thermal comfort and energy performance of educational buildings. Specifically, the analysis was made for the south-oriented classroom during the occupied hours. The south orientation demonstrated the worst-case classroom in terms of thermal comfort and for this reason it was selected as a representative case for the analysis. The adaptation measures concerning the architectural elements such as the shading devices may have different impact on the thermal, energy and economic performance of classrooms with different orientations. However, due to the scale of the present study it was difficult to analyse in a greater extend the impact of different shading devices.

The last limitation concerns the evaluation of air quality in educational buildings. Specifically, the present thesis evaluated the indoor air quality using the indicator of $CO_2$ concentration, which is the most used indicator of ventilation efficiency. However, various other pollutants such as bacteria, mould, volatile organic compounds (VOCs), allergens, particulate matter (PM) etc. can be used to evaluate the air quality of a space. However, these pollutants need specific equipment for the measurements that were not available at by the Environmental Lab of the University of Cyprus. In addition to this, the ventilation rate achieved through the examination of different ventilation rates was not measured directly as the method used for that measurement is the tracer gas method which is difficult to be applied during the normal operation of educational buildings.

## 18.5. Significance, opportunities and potential directions for further research

It has become evident that Southern Europe will experience more adverse climate change effects compared to other European regions. The existing educational building stock, which can largely be described as free-running, is expected to have a significant impact on users' thermal comfort, well-being and productivity. This research has addressed several topical issues in the field of comfort and energy performance under the current and future climatic conditions.

The research indicates that educational buildings in southern Europe in their current condition are unable to meet the comfort criteria both in the current and future climate, which entails a major impact on the environmental, economic and social interaction of people and buildings. The emerging problem is related to the deterioration of comfort and well-being in public school classrooms especially during the late spring and early autumn days because of high temperatures and high concentration of people in classrooms (thermal), during the winter period due to high concentration of people in classroom and the need to reduce heat losses keeping classroom closed (air quality), and during the entire year because some classrooms suffer from glare issues (lighting).

The majority of school buildings in Cyprus that were constructed without meeting the requirements for energy efficiency, are characterized by great standardization in design, structure, construction, and typology and offer many possibilities of application for simple bioclimatic principles.

On this basis, methods and practices have been sought which bring about a sustainable solution to the problem with respect to the anthropogenic and natural environment. Moreover, creating healthy school environments can influence the health and academic success and productivity of children. This thesis highlighted the importance of natural ventilation for both thermal comfort and air quality and examined its potential in a great extent in order to quantify its contribution in the specific climatic conditions and specific typology of buildings. This study will help local government to reduce costs, remain resilient and fulfil their role in protecting users and infrastructure. The key is to maintain a balance between thermal comfort, visual comfort, air quality and energy performance. The proposed aforementioned strategies take into account each field of comfort and trying to minimize the influence they can have on each other.

Based on the existing literature review, studies on thermal comfort in educational buildings are scarce compared to the broader academic field of comfort studies. The growing number of studies in the field increases the chances of covering the majority of issues related to comfort, overcoming the limitations and giving valuable knowledge about drawing valid conclusions regarding the best way to design or give feedback related to buildings designed for teaching and learning. Therefore, this study aims to contribute to the literature regarding the educational buildings in the Eastern-Mediterranean region as well as influencing policies.

Additionally, research studies that emphasize the impact of climate change on buildings are limited and the relevant literature indicates that there are difficulties for direct comparison of the energy consumption between buildings due to variations in the climatic conditions, building characteristics and operation. Specifically, there are no available studies that focus on the impact of climate change on the thermal and energy performance of educational buildings in Cyprus. The study thus, contributes to delivering novel knowledge in the relevant field and assesses the potential and effectiveness of adaptation measures both during current and future climatic conditions.

This thesis developed a multi-criteria methodology for the evaluation of existing educational buildings, as well as for the evaluation of sustainable adaptation measures that can be used for any kind of building in all climatic conditions. Moreover, the results derived from this thesis provided energy retrofit option ranking with life-cycle costing analysis and gave useful data for the development of a methodology to support decision making for the upgrade and decarbonisation of existing educational building stock that takes into account comfort, energy upgrading and adaptation to climate change. Taking into account that similar building arrangements of linear disposition of classrooms, connected with semi-open corridors like the ones mentioned in this study and that are commonly found in other countries of the Eastern Mediterranean region that share similar climatic conditions with Cyprus, the results of the current study can be applied in a wider sample of buildings.

Finally, it should highlighted that part of the results of the present thesis has been presented in the Ministry of Education in the in the framework of regular meetings of an interdisciplinary committee under the coordination of the Head of Technical Services of the Ministry of Education, Culture, Sport and Youth, in which discussed the problem that arises in the last weeks of spring and the early weeks of autumn with the temperature in the classrooms and the worsening of comfortable conditions in the classrooms of public schools due to their structural characteristics and the high concentration of students. The findings of this study prevented the installation of spilt units air conditioning in the educational buildings for the provision of thermal comfort and at the same time promoted at the same time environmental friendly solutions relevant to the guidelines derived from this thesis.

At the same time, the research team of the Laboratory of Energy and Environmental Design of Buildings of the University of Cyprus (including the author) in collaboration with the Technical Services of the Ministry of Education, Culture, Sports and Youth has submitted a proposal under the 4th call for proposals in European Territorial Cooperation Programme Interreg V-A-Greece-Cyprus 2014-2020, for the implementation of adaptation measures in the educational building used in this study as a representative reference building, with title “Cooperative Intelligent education & electromobility in Zero Energy Buildings "with acronym" C-IZEBs”. The proposal has been approved for funding by the European Union and therefore the University of Cyprus with the Ministry of Education will jointly present the comprehensive proposal to address the issue of poor energy efficiency and low comfort levels in educational buildings in Cyprus. The operation of this application will be continuously monitored, after the implementation of the proposed actions, in order to evaluate in real conditions the results of the interventions and to identify possible points for further improvement. The proposed project will contribute to the detailed information of all stakeholders and social groups on this issue and will create conditions for energy education and environmental awareness to users of school buildings and society as a whole as schools are among the most promising public building types to act as lighthouse projects. Classroom interventions can offer pupils hands-on experience on visible improvements to the building envelope, and encourage them to support energy savings and indoor air quality by responsible user behaviour.

Apart from the research programme, the Ministry of Education, Culture, Sport and Youth suggest a substantial cooperation to the Laboratory of Energy and Environmental Design of Buildings of the University of Cyprus for the holistic upgrade of Educational Buildings in Cyprus, based on the guidelines derived from this thesis, making the impact of this thesis even greater in the society eliminate at the same time the energy consumption $CO_2$ emissions, climate change and global warming.

After answering the research questions posed by this thesis and addressing the gaps and limitations in the literature recapitulated in this chapter, several new questions for future research to answer are formulated. The following suggestions and potential directions for further research emerge from this study:

1. To extend the multi-criteria methodology of the present study across different contexts and building types. A quantitative study through field measurements and software simulation and qualitative study through questionnaire can be adopted in future research as a standard technique to assess the comfort and energy performance in other building types and settings.

2. To further validate the present findings about the impact of climate change and proposed improvements on educational buildings of other climatic zones. The present study focused on the climatic zone 2 which is the lowland area. It would be interesting to investigate whether the impact of climate change affects in a similar way the educational buildings of Cyprus elsewhere. Additionally, although the proposed measures are applicable to all climatic zones, it would be interesting to validate the results in educational buildings of all climatic zones and investigate if the small climatic variations affect the performance of measures.

3. To address the limitation of this study in the future research and investigate the impact of different shading devices on comfort conditions and energy performance. Due to the scale of the present study it was difficult to analyse in a great extent all the available different shading devices, which incorporate different angles and widths. This area could be an independent future comprehensive study about the effects of shading on both comfort and energy performance.

4. To further confirm the present findings of adaptation measures under the use of different climate change projections. The choice of the climatic scenario A1B was based on the intermediate case,

which lies in the middle of the 'business as usual' scenario and the 'united sustainable planet' extremes [6]. The A1B scenario was well suited for the study purposes and is in line with the claims of the present study. It would be interesting to see what impacts other milder or more extreme climatic projections cause on comfort conditions and energy performance of educational buildings and at what extent adaptation measures can meet thermal and energy requirements.

5. To further confirm, explore and derive a better understanding about the acceptable range of temperatures based on thermal sensation, preference and satisfaction of students in relation to the outdoor climate. This could be achieved using greater number of sample of subjects and monitoring periods and measuring other affecting parameters such as clothing insulation values, by identifying student's resting metabolism and activity levels and by measuring the two physiological variables i.e., skin temperature and sweat rates.

## 18.6. Epilogue

School buildings are one of the most demanding categories of buildings in terms of occupant comfort requirements. In addition, there is a particular need in ensuring adequate occupant conditions for educational buildings, arises from the large number of people, the significant percentage of daily time and the importance of the school building, in terms of its own educational program, learning and development.

The multitude of parameters that constitute the concept of overall comfort in the school building, make its clear qualitative and quantitative determination, complex. The results of the present study, however, provide a multi-criteria evaluation model in terms of overall comfort and energy efficiency conditions together with a series of proposals for upgrading the school building stock. In addition to upgrading existing standard school buildings, methodological tools for designing new school complexes are provided. Through this process, the enrichment of the architectural creation is sought with new parameters, design and construction tools, which allow the most complete, in terms of comfort, approach to school architecture.

Climate change will lead to increased overheating days that will significantly affect the indoor comfort conditions and energy performance of buildings. This need for adaptation goes beyond just the 'hot' countries of the Mediterranean; and solutions to climate resilience and adaptation are becoming more urgent in countries across the globe. For that reason, decision-makers at the level of Ministry must both support and promote capacity building, to anticipate and effectively plan for climate change, by addressing local institutional challenges. This will in turn enhance the ability of building professionals to perform practical adaptation strategies, and support systems, in order to maintain crucial services and improve community readiness for climate variability in general.

With the global spread of the Covid-19 pandemic in the world, due to high prevalence and high mortality rate, it seems that having a healthy living environment is one of the main concerns of the people from several aspects. Educational spaces have become dramatically important in terms of controlling pandemics and as an environment that must meet the needs of adequate indoor air quality making the contribution of this research even greater.

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# Appendices

## Appendix A: Granting permission to conduct research in schools from the Ministry of Education and Culture, Secondary General Education

ΚΥΠΡΙΑΚΗ ΔΗΜΟΚΡΑΤΙΑ

**ΥΠΟΥΡΓΕΙΟ ΠΑΙΔΕΙΑΣ ΚΑΙ ΠΟΛΙΤΙΣΜΟΥ**

**ΔΙΕΥΘΥΝΣΗ ΜΕΣΗΣ ΕΚΠΑΙΔΕΥΣΗΣ**

Αρ. Φακ.: 7.15.01.25.8.2/5
Αρ. Τηλ.: 22800664
Αρ. Φαξ: 22428268
E-mail: circularsec@schools.ac.cy

17 Νοεμβρίου 2017

Κυρία Χρύσω Ηρακλέους
Αγίου Ιουστίνου 4
2055 Στρόβολος

**Θέμα: Παραχώρηση άδειας για διεξαγωγή έρευνας**

Αναφορικά με τη σχετική με το πιο πάνω θέμα αίτησή σας στο Κέντρο Εκπαιδευτικής Έρευνας και Αξιολόγησης, ημερομηνίας 1/11/2017, πληροφορείστε ότι το αίτημά σας για διεξαγωγή έρευνας, με θέμα «*Προσέγγιση αναβάθμισης του κτιριακού αποθέματος σχολικών κτιρίων και οι επιπτώσεις στην κατανάλωση ενέργειας*», στα πλαίσια έρευνας για την απόκτηση του διδακτορικού τίτλου σπουδών στο Πανεπιστήμιο Κύπρου, εγκρίνεται. Νοείται ότι θα λάβετε υπόψη τις εισηγήσεις του Κέντρου Εκπαιδευτικής Έρευνας και Αξιολόγησης οι οποίες επισυνάπτονται, και ότι θα τηρήσετε τις ακόλουθες προϋποθέσεις:

1. θα εξασφαλίσετε τη συγκατάθεση των Διευθυντών/-ντριών των Σχολείων τα οποία θα συμμετάσχουν στην έρευνα,
2. η συμμετοχή των μαθητών θα είναι προαιρετική,
3. θα εξασφαλίσετε τη γραπτή συγκατάθεση των γονέων των μαθητών οι οποίοι θα συμμετάσχουν στην έρευνα,
4. δε θα επηρεασθεί ο διδακτικός χρόνος και η ομαλή λειτουργία του σχολείου για τη διεξαγωγή της έρευνας,
5. θα χειριστείτε τα στοιχεία των εμπλεκομένων με τέτοιο τρόπο, ώστε να διασφαλιστεί πλήρως η ανωνυμία τους,
6. για τη χρήση μαγνητοφώνου ή οποιασδήποτε άλλης μεθόδου για τυχόν καταγραφή ήχου ή εικόνας, θα πρέπει να πάρετε άδεια γραπτώς από τους εμπλεκόμενους οι οποίοι θα συμμετάσχουν καθώς και από τους γονείς τους, και τέλος,
7. τα αποτελέσματα της έρευνας θα κοινοποιηθούν στο Υπουργείο Παιδείας και Πολιτισμού και στα σχολεία που θα σας παραχωρήσουν διευκολύνσεις για τη διεξαγωγή της.

Ευχόμαστε καλή επιτυχία στους ερευνητικούς σας σκοπούς.

α.α. Tm.

Δρ Κυπριανός Δ. Λούης
Διευθυντής Μέσης Εκπαίδευσης

Κοιν.: Διευθύντρια Γυμν. Αρχ. Μακαρίου Γ' (Πλατύ)

ΒΚ

*Υπουργείο Παιδείας και Πολιτισμού* 1434 Λευκωσία
Τηλ: 22 800 600 fax: 22 428268 website: www.moec.gov.cy

## Appendix B: Authorisation to conduct research in Archbishop Makarios III Secondary School granted by the School District office of Aglantzia

ΣΧΟΛΙΚΗ ΕΦΟΡΕΙΑ
ΑΓΛΑΝΤΖΙΑΣ
1992

**Αρ. Πρωτ.:**315/Π.Ξ/82.

30 Ιανουαρίου 2018

**Κυρία Χρύσω Ηρακλέους**
Πανεπιστήμιο Κύπρου
Email: echryso@ucy.ac.cy; on behalf of; Chryso Heracleous
[heracleous.chryso@ucy.ac.cy]

**<u>Θέμα:</u> Παραχώρηση άδειας εισόδου στο Γυμν. Πλατύ εκτός ωρών λειτουργίας του σχολείου για διεξαγωγή έρευνας**

Αναφορικά με το πιο πάνω θέμα σας ενημερώνουμε ότι η Σχολική Εφορεία Αγλαντζιάς ενέκρινε το αίτημά σας για παραχώρηση των αιθουσών 35, 36, 37 και 38 για συγκεκριμένα Σαββατοκύριακα καθώς επίσης και κάποιες βραδινές ώρες για τη διεξαγωγή έρευνας για διερεύνηση του νυχτερινού αερισμού.
Παρακαλούμε όπως ληφθούν σοβαρά υπόψη σας τα ακόλουθα:

- Θα πρέπει όμως να είστε πολύ προσεκτική και να λάβετε όλα τα μέτρα ώστε να αποφευχθεί η είσοδος σε ξένα άτομα στο χώρο του σχολείου.
- Να διατηρηθούν οι αίθουσες καθαρές και να μη μετακινηθεί ο οποιοσδήποτε εξοπλισμός των τάξεων.
- Η Σχολική Εφορεία δεν θα φέρει καμιά ευθύνη σε περίπτωση τυχόν ατυχήματος, θα είστε υπεύθυνη εσείς για την ασφάλειά σας.

Για οτιδήποτε χρειαστείτε, να απευθύνεστε στη Διευθύντρια του πιο πάνω σχολείου.

Με εκτίμηση

Κώστας Παπακυπριανού
Πρόεδρος

ΣΧΟΛΙΚΗ ΕΦΟΡΕΙΑ ΑΓΛΑΝΤΖΙΑΣ 1992

Μυρούλα Λάμπρου
Γραμματέας

**<u>Κοιν.</u>:** Διευθυντή Γυμνασίου Πλατύ

Ε.Γ./Εφορεία 2017-2018 - Π.Ξ.

*ΤΑΧ. ΘΥΡΙΔΑ: 20266, 2150 ΛΕΥΚΩΣΙΑ – ΤΗΛ. 22333847, 22340260, ΦΑΞ: 22337901*

**ΣΧΟΛΙΚΗ ΕΦΟΡΕΙΑ ΑΓΛΑΝΤΖΙΑΣ**

1992

**Αρ. Πρωτ.:**579/Π.Ξ/118

8 Μαΐου 2018

Κύριο Αιμίλιο Μιχαήλ, Αρχιτέκτονας
**Υπόψη κας Χρύσω Ηρακλέους**
Πανεπιστήμιο Κύπρου
Email: echryso@ucy.ac.cy; on behalf of; Chryso Heracleous [heracleous.chryso@ucy.ac.cy]
Φαξ: 22895056

**Θέμα: Παραχώρηση άδειας εισόδου στο Γυμν. Πλατύ εκτός ωρών λειτουργίας του σχολείου για διεξαγωγή έρευνας**

Αναφορικά με το πιο πάνω θέμα σας ενημερώνουμε ότι η Σχολική Εφορεία Αγλαντζιάς ενέκρινε το αίτημά σας για παραχώρηση από τις 12-15 Μαΐου 2018 των αιθουσών 35, 36, 37 και 38 για το Σαββατοκύριακο καθώς επίσης και κάποιες βραδινές ώρες για τη διεξαγωγή έρευνας για διερεύνηση του νυχτερινού αερισμού.
Παρακαλούμε όπως ληφθούν σοβαρά υπόψη σας τα ακόλουθα:

- Θα πρέπει όμως να είστε πολύ προσεκτική και να λάβετε όλα τα μέτρα ώστε να αποφευχθεί η είσοδος σε ξένα άτομα στο χώρο του σχολείου.
- Να διατηρηθούν οι αίθουσες καθαρές και να μη μετακινηθεί ο οποιοσδήποτε εξοπλισμός των τάξεων.
- Η Σχολική Εφορεία δεν θα φέρει καμιά ευθύνη σε περίπτωση τυχόν ατυχήματος, θα είστε υπεύθυνη εσείς για την ασφάλειά σας.

Για οτιδήποτε χρειαστείτε, να απευθύνεστε στη Διευθύντρια του πιο πάνω σχολείου.

Με εκτίμηση

Κώστας Παπακυπριανού
Πρόεδρος

ΣΧΟΛΙΚΗ ΕΦΟΡΕΙΑ ΑΓΛΑΝΤΖΙΑΣ 1992

Μυρούλα Λάμπρου
Γραμματέας

**Κοιν.:** Διευθυντή Γυμνασίου Πλατύ

Ε.Γ./Εφορεία 2017-2018 - Π.Ξ.

*ΤΑΧ. ΘΥΡΙΔΑ: 20266, 2150 ΛΕΥΚΩΣΙΑ – ΤΗΛ. 22333847, 22340260, ΦΑΞ: 22337901*

## Appendix C: Granting permission for the questionnaire from Educational Research and Evaluation Centre

K.E.E.A. Κέντρο Εκπαιδευτικής Έρευνας και Αξιολόγησης | Νοέμβριος 2017

### Σχόλια για ερευνητικές προτάσεις

| | |
|---|---|
| Θέμα έρευνας: | Διερεύνηση Συνθηκών Περιβαλλοντικής Άνεσης και Λειτουργίας των Σχολικών Κτιρίων στα πλαίσια διδακτορικής διατριβής με τίτλο "Προσέγγιση αναβάθμισης του κτιριακού αποθέματος σχολικών κτιρίων και οι επιπτώσεις στην κατανάλωση ενέργειας" |
| Κωδικός έρευνας: | 130911 |
| Ονοματεπώνυμο Ερευνητή: | Ηρακλέους Χρύσω |
| Διεύθυνση στην οποία υποβλήθηκε: | Διεύθυνση Δημοτικής Εκπαίδευσης<br>Διεύθυνση Μέσης Εκπαίδευσης |
| Ημερομηνία υποβολής στο ΚΕΕΑ: | 06/11/2017 |

1. **Σκοπός -ερευνητικά ερωτήματα/υποθέσεις**

   Δεν υπάρχουν παρατηρήσεις.

2. **Χρησιμότητα-αναγκαιότητα της έρευνας**

   Δεν υπάρχουν παρατηρήσεις.

3. **Διαδικασία συλλογής δεδομένων**

   Δεν υπάρχουν παρατηρήσεις.

4. **Δειγματοληψία**

   Δεν υπάρχουν παρατηρήσεις.

5. **Ερευνητικά εργαλεία**

   Δεν υπάρχουν παρατηρήσεις.

6. **Χρόνος απασχόλησης**

   Δεν υπάρχουν παρατηρήσεις.

1

**7. Χρονική περίοδος έρευνας και αναμενόμενος χρόνος αποτελεσμάτων**

Δεν υπάρχουν παρατηρήσεις.

**8. Θέματα ηθικής και ερευνητικής δεοντολογίας**

Δεν υπάρχουν παρατηρήσεις.

**9. Εισήγηση ΚΕΕΑ**

| | |
|---|---|
| Η έρευνα να προχωρήσει ως έχει για υλοποίηση | √ |
| Η έρευνα να προχωρήσει για υλοποίηση, νοουμένου ότι θα γίνουν οι αλλαγές/τροποποιήσεις/εισηγήσεις που επισημαίνονται πιο πάνω | |
| Η αίτηση για έρευνα να υποβληθεί ξανά αφού ληφθούν υπόψη τα πιο πάνω | |

2

## Appendix D: Information and consent form for the parent-guardian association

Πανεπιστήμιο Κύπρου
Τμήμα Αρχιτεκτονικής

Κτίριο Λήδρας, Όδος Αριάδνης 23Α και Λήδρας 68, 1010 Λευκωσία
Τηλ. 22892960 / 22892980 – Τηλεομ. 22895056 – E-mail: Architecture@ucy.ac.cy

---

ΠΡΟΣ : Σύνδεσμό Γονέων και Κηδεμόνων Γυμνασίου Αρχ. Μακαρίου Γ'

ΑΠΟ : Αιμίλιο Μιχαήλ
Λέκτορα, Τμήμα Αρχιτεκτονικής, Πανεπιστήμιο Κύπρου

ΗΜΕΡ. : 11 Δεκεμβρίου 2017

ΘΕΜΑ : Συμπλήρωση ερωτηματολογίων και εγκατάσταση οργάνων μέτρησης εσωτερικών συνθηκών για την αξιολόγηση των συνθηκών άνεσης των εκπαιδευτικών κτιρίων με στόχο την εξεύρεση βέλτιστών στρατηγικών για το φυσικό δροσισμό και την ποιότητα αέρα των αιθουσών διδασκαλίας

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Στα πλαίσια της διδακτορικής διατριβής της κυρίας Ηρακλέους, που εκπονείται στο Τμήμα Αρχιτεκτονικής του Πανεπιστημίου Κύπρου και έχει ως θέμα: «Προσαρμοστικότητα στην κλιματική αλλαγή: Προσέγγιση αναβάθμισης του κτιριακού αποθέματος σχολικών κτιρίων και οι επιπτώσεις στην κατανάλωση ενέργειας», απαιτείται η αξιολόγηση των συνθηκών άνεσης των εκπαιδευτικών κτιρίων και η διερεύνηση των βέλτιστων στρατηγικών για φυσικό δροσισμό και ποιότητα αέρα μέσω αερισμού.

Τα επίπεδα αερισμού στα σχολεία επηρεάζουν τη θερμική άνεση, την ποιότητα του αέρα του εσωτερικού χώρου, την υγεία και έμμεσα την ικανότητα εκμάθησης και τις επιδόσεις των μαθητών. Η θετική συνεισφορά του φυσικού αερισμού στην βελτίωση της ποιότητας εσωτερικού αέρα, στη θερμικής άνεσης και στην εξοικονόμηση ενέργειας τονίζονται σε διάφορες μελέτες.

Η διερεύνηση της θερμικής συμπεριφοράς και η αναζήτηση των βέλτιστων στρατηγικών φυσικού αερισμού θα πραγματοποιηθεί με επιτόπου καταγραφή των περιβαλλοντικών παραμέτρων σε ένα τυπικό σχολείο Μέσης Εκπαίδευσης. Η διερεύνηση θα αφορά διαφορετικά πρότυπα και είδη αερισμού που θα εξετάζονται σε διαφορετικούς προσανατολισμούς και διαφορετικές εποχές του χρόνου για περίπου μια βδομάδα ανά εποχή.

Παράλληλα θα διανεμηθεί ερωτηματολόγιο για την αξιολόγηση των συνθηκών άνεσης στα σχολεία εγκεκριμένο από το Κέντρο Εκπαιδευτικής Έρευνας και Αξιολόγησης του Υπουργείου Παιδείας και Πολιτισμού. Το ερωτηματολόγιο θα συμπληρωθεί από μαθητές και εκπαιδευτικούς σχολικών κτιρίων για την αξιολόγηση θερμικής άνεσης σε σχολεία και την καταγραφή/παρατήρηση της συμπεριφοράς των χρηστών για προσαρμογή στις κλιματολογικές συνθήκες με στόχο την διερεύνηση των βέλτιστων στρατηγικών φυσικού δροσισμού και ποιότητας αέρα μέσω αερισμού.

Ο απαιτούμενος χρόνος συμπλήρωσης του ερωτηματολογίου είναι 10 λεπτά και είναι ανώνυμο. Η συμμετοχή στην έρευνα είναι εθελοντική και οι συμμετέχοντες έχουν δικαίωμα να διακόψουν την συμπλήρωση του ερωτηματολογίου οποιαδήποτε στιγμή το επιθυμήσουν χωρίς συνέπειες. Οι συμμετέχοντες θα μπορούν να αποχωρήσουν αποσύροντας τα δεδομένα που θα έχουν δώσει μέχρι τη στιγμή αυτή. Η έρευνα προϋποθέτει την σύμφωνη γνώμη του παιδιού ανεξάρτητα από την συγκατάθεση που έχει δώσει ο γονέας/κηδεμόνας στο παιδί του. Δεν θα υπάρχει οποιαδήποτε μορφή μαγνητοφώνησης ή βιντεοσκόπησης των συμμετεχόντων για την καταγραφή των δεδομένων. Το ερωτηματολόγιο θα συμπληρωθεί όταν τα παιδιά βρίσκονται στις τάξεις τους με την παρουσία εκπαιδευτικού του σχολείου. Διαβεβαιώνεται ότι τα δεδομένα που θα συλλεγούν θα χρησιμοποιηθούν μόνο για σκοπούς της συγκεκριμένης έρευνας και θα ληφθούν όλα τα απαραίτητα μέτρα για την ασφαλή φύλαξη των δεδομένων της έρευνας. Σε ότι αφορά στη χρονική περίοδο συλλογής των δεδομένων, σημειώνεται ότι τα ερωτηματολόγια θα συμπληρωθούν σε 3 διαφορετικές εποχές του χρόνου για εξασφάλιση της αξιοπιστία των αποτελεσμάτων.

Σε ότι αφορά στο περιεχόμενο του ερωτηματολογίου, αρχικά υπάρχουν κάποιες γενικές πληροφορίες σε ότι αφορά δημογραφικά δεδομένα. Στην συνέχεια υπάρχουν ερωτήσεις που αφορούν στις συνθήκες θερμικής άνεσης. Τέλος, οι ερωτήσεις αφορούν στην λειτουργία του κτιρίου από τους χρήστες.

Σημειώνεται ότι το ερωτηματολόγιο έχει εγκριθεί από το Κέντρο Εκπαιδευτικής Έρευνας και Αξιολόγησης του Υπουργείου Παιδείας και Πολιτισμού. Για την εγκατάσταση σχετικού εξοπλισμού καταγραφής περιβαλλοντικών δεδομένων έχουν γίνει όλα τα απαιτούμενα διαβήματα προς τη Διεύθυνση Μέσης Εκπαίδευσης και τις Τεχνικές Υπηρεσίες του Υπουργείου Παιδείας και Πολιτισμού.

Επισυνάπτεται έντυπο συγκατάθεσης του γονέα/κηδεμόνα όπου θα πρέπει να συμπληρωθεί για κάθε παιδί του σχολείου και να επιστραφεί στην ερευνήτρια. Στο έντυπο συγκατάθεσης θα πρέπει να συμπληρωθούν το ονοματεπώνυμο, το σχολείο, το τμήμα και η τάξη του παιδιού. Σημειώνεται ότι το παρόν έντυπο ενημέρωσης του γονέα/κηδεμόνα υποβάλλεται για ενημέρωση του γονέα/κηδεμόνα και δεν θα επιστραφεί στην ερευνήτρια.

Για το σκοπό αυτό, παρακαλώ θερμά για την συγκατάθεση σας στην εκπόνηση της συγκεκριμένης ερευνάς.

Για οποιεσδήποτε πληροφορίες παρακαλώ επικοινωνήστε με την ερευνήτρια Χρύσω Ηρακλέους, τηλ. 99682291, email: echryso@ucy.ac.cy.

Σε περίπτωση υποβολής παραπόνου ή καταγγελίας παρακαλώ επικοινωνήστε με τη λειτουργό της Υπηρεσίας Υποστήριξης Έρευνας του Πανεπιστημίου Κύπρου, Χριστίνα Δελαπόρτα τηλ. 22895146, email: delaporta.christina@ucy.ac.cy.

Με εκτίμηση,

Αιμίλιος Μιχαήλ, Αρχιτέκτονας, M.Arch., M.Sc., Ph.D. NTUA.
Λέκτορας, Τμήμα Αρχιτεκτονικής, Πανεπιστήμιο Κύπρου.
aimilios@ucy.ac.cy
Τηλ. + 357 22 892977
Φαξ +357 22 895056

Πανεπιστήμιο Κύπρου
Τμήμα Αρχιτεκτονικής

Κτίριο Λήδρας, Όδος Αριάδνης 23Α και Λήδρας 68, 1010 Λευκωσία

Τηλ. 22892960 / 22892980 – Τηλεομ. 22895056 – E-mail: Architecture@ucy.ac.cy

***ΕΝΤΥΠΟ ΣΥΓΚΑΤΑΘΕΣΗΣ ΓΟΝΕΩΝ ΓΙΑ ΤΗΝ ΣΥΜΠΛΗΡΩΣΗ ΕΡΩΤΗΜΑΤΟΛΟΓΙΩΝ***

Στα πλαίσια της διδακτορικής διατριβής που εκπονείται στο Τμήμα Αρχιτεκτονικής του Πανεπιστημίου Κύπρου και έχει ως θέμα: «Προσαρμοστικότητα στην κλιματική αλλαγή: Προσέγγιση αναβάθμισης του κτιριακού αποθέματος σχολικών κτιρίων και οι επιπτώσεις στην κατανάλωση ενέργειας», θα πραγματοποιηθεί η αξιολόγηση των συνθηκών άνεσης των εκπαιδευτικών κτιρίων μέσω της διερεύνησης των βέλτιστων στρατηγικών για φυσικό δροσισμό και ποιότητας αέρα.

Είναι σημαντικό να αναφερθεί ότι τα επίπεδα αερισμού στα σχολεία επηρεάζουν τη θερμική άνεση, την ποιότητα του αέρα του εσωτερικού χώρου, την υγεία και έμμεσα την ικανότητα εκμάθησης και τις επιδόσεις των μαθητών.

Με τη παρούσα συγκατατίθεμαι ότι το παιδί μου …………………………………………….. (ονοματεπώνυμο) που φοιτάει στο Σχολείο ……………………………………………….και στο τμήμα …………………….. να συμπληρώσει το ερωτηματολόγιο με τίτλο «Συνθήκες Περιβαλλοντικής Άνεσης και Λειτουργίας των Σχολικών Κτιρίων». Σημειώνεται ότι η συμπλήρωση του ερωτηματολογίου θα γίνει σε τρεις χρονικές φάσεις για την εξασφάλιση της αξιοπιστία των αποτελεσμάτων.

Παρακαλώ όπως το παρόν έντυπο επιστραφεί μέχρι τις 20 Δεκεμβρίου 2017 στην ερευνήτρια.

Στη διάθεση σας για οποιαδήποτε διευκρίνηση.

Υπογραφή: ………………………………………...

Ονοματεπώνυμο: …………………………………..

Στοιχεία Επικοινωνίας:

Χρύσω Ηρακλέους, τηλ. 99682291, email: echryso@ucy.ac.cy

# Appendix E: Sample of field research questionnaire of this thesis

Πανεπιστήμιο Κύπρου
Τμήμα Αρχιτεκτονικής

ΕΡΩΤΗΜΑΤΟΛΟΓΙΟ

## ΣΥΜΠΛΗΡΩΣΗ ΕΡΩΤΗΜΑΤΟΛΟΓΙΟΥ

**«Συνθήκες Περιβαλλοντικής Άνεσης και Λειτουργίας των Σχολικών Κτιρίων» στα πλαίσια εκπόνησης διδακτορικής διατριβής με τίτλο «Προσαρμοστικότητα στην κλιματική αλλαγή: Προσέγγιση αναβάθμισης του κτιριακού αποθέματος σχολικών κτιρίων και οι επιπτώσεις στην κατανάλωση ενέργειας».**

- Το ερωτηματολόγιο πραγματοποιείται με σκοπό τη μελέτη περιβαλλοντικών συνθηκών στα σχολικά κτίρια.
- Το ερωτηματολόγιο είναι ανώνυμο.
- Η συμμετοχή στην έρευνα είναι εθελοντική και οι συμμετέχοντες/ουσες μπορούν να αποχωρήσουν οποιαδήποτε στιγμή από την έρευνα χωρίς συνέπειες.
- Τα δεδομένα που θα συλλεγούν θα χρησιμοποιηθούν μόνο για σκοπούς της συγκεκριμένης έρευνας.
- Ο απαιτούμενος χρόνος συμπλήρωσης του ερωτηματολογίου είναι 10 λεπτά.
- Παρακαλώ σημειώστε ✓στην κατάλληλη απάντηση.

Πανεπιστήμιο Κύπρου
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ΕΡΩΤΗΜΑΤΟΛΟΓΙΟ

**Σημείωση: Θα δίνονται οδηγίες προφορικά εάν αυτό απαιτείται από τους συμμετέχοντες**

**Ημερομηνία:**...................................... **Σχολείο:** ...................................................................................
**Ώρα:** .................. **Περίοδος:**............... **Προσανατολισμός εισόδου τάξης: Α / Δ / Β / Ν**

**Α. ΓΕΝΙΚΕΣ ΠΛΗΡΟΦΟΡΙΕΣ**

**1. Ηλικία:**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Παιδί 6-9 | | 9-12 | | 12-15 | | 15-18 | |
| Καθηγ. 25-34 | | 35-44 | | 45-54 | | >55 | |

**2. Εκπαίδευση:**

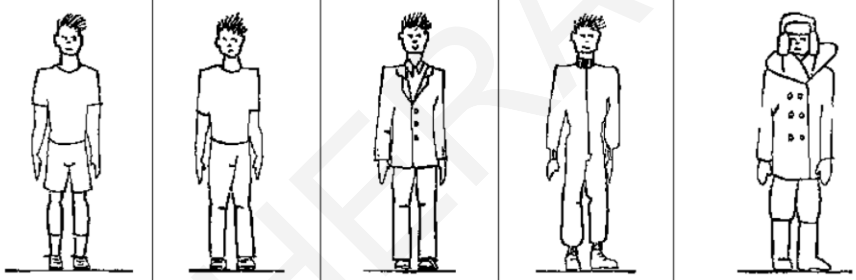
| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Δημοτικό | | Γυμνάσιο | | Λύκειο | | Άλλο | |

**3. Φύλο:**

Άντρας/ Αγόρι ☐

Γυναίκα/ Κορίτσι ☐

**4. (α) Σημειώστε ✓ στην εικόνα που ανταποκρίνεται στην ενδυμασία σας**



| | | | | |
|---|---|---|---|---|
| | | | | |

**(β) Τί ρούχα φοράω αυτή τη στιγμή;**

| | | | |
|---|---|---|---|
| Αμάνικη μπλούζα ή πουκάμισο | | Πουλόβερ - Ζακέτα | |
| Κοντομάνικη μπλούζα ή πουκάμισο | | Σακάκι | |
| | | | |
| Κοντό παντελόνι ή φούστα | | Φόρεμα κοντό | |
| Μακρύ παντελόνι ή τζιν | | Φόρεμα μακρύ | |
| | | | |
| Σάρπα | | Παπούτσια και κάλτσες | |
| Καπέλο ή σκούφος | | Σανδάλια | |
| | | | |
| Καλσόν | | Γραβάτα | |

**5. Είμαι καπνιστής:**

Ναι ☐

Όχι ☐

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ΕΡΩΤΗΜΑΤΟΛΟΓΙΟ

**Β. ΣΥΝΘΗΚΕΣ ΘΕΡΜΙΚΗΣ ΑΝΕΣΗΣ**

1. **Την τελευταία μισή ώρα κατανάλωσα κάποιο:**
   Κρύο ποτό ☐ Κρύο Σνακ ☐
   Ζεστό ποτό ☐ Ζεστό Σνακ ☐
2. **Την τελευταία μισή ώρα κατά κύριο λόγο:**
   Καθόμουν ☐ Στεκόμουν ☐
   Περπατούσα ☐ Έτρεχα ☐
3. **Πριν επισκεφτώ αυτό το μέρος βρισκόμουν σε:**
   Αυλή ☐ Αίθ. Πολλαπλών ☐ Βεράντα ☐
   Εργαστήριο ☐ Τάξη/Αίθουσα ☐ Όχημα ☐
4. **Στο σχολείο έφτασα με:**
   Πόδια ☐ Ποδήλατο ☐ Λεωφορείο ☐ Αυτοκίνητο ☐
5. **Παρακαλώ δηλώστε πώς νιώθετε αυτή τη στιγμή:**

| Πολύ κρύο | Κρύο | Ελαφρώς κρύο | Ούτε κρύο, ούτε ζέστη | Ελαφρώς ζέστη | Ζέστη | Πολλή ζέστη |
|---|---|---|---|---|---|---|
| | | | | | | |

6. **Θα ήθελα να είναι:**

| Πολύ πιο ζεστά | Λίγο πιο ζεστά | Καμία αλλαγή | Λίγο πιο δροσερά | Πολύ πιο δροσερά |
|---|---|---|---|---|
| | | | | |

7. **Θα προτιμούσα:**

| Πολύ λιγότερο άνεμο | Λιγότερο άνεμο | Καμία αλλαγή | Περισσότερο άνεμο | Πολύ περισσότερο άνεμο |
|---|---|---|---|---|
| | | | | |

8. **Αυτή τη στιγμή:**
   Αισθάνομαι θερμικά άνετα ☐
   Δεν αισθάνομαι θερμικά άνετα ☐ *Θα εξηγηθεί προφορικά εάν απαιτηθεί
9. **Πόσο ικανοποιημένος είμαι με το χώρο της τάξης μου:**
   Καθόλου ☐ Λίγο ☐ Μέτρια ☐ Αρκετά ☐ Πολύ ☐
10. **Κάτι που ΔΕΝ μου αρέσει στη τάξη (επιλέξετε όσα ισχύουν):**
    Καθαριότητα ☐ Ανεπαρκής φωτισμός ☐
    Θόρυβος ☐ Κακή αισθητική του χώρου ☐
    Δυσάρεστες οσμές ☐ Άλλο (……………………………) ☐

**Γ. ΣΥΝΘΗΚΕΣ ΠΟΙΟΤΗΤΑΣ ΑΕΡΑ**

**Πώς αξιολογείτε την** ΠΟΙΟΤΗΤΑ ΑΕΡΑ **του κτιρίου;**

**α. Ποιότητα αέρα** Ξηρός ☐☐☐☐☐ Υγρός

**β.** Φρέσκος ☐☐☐☐☐ 'Βαρύς'

Πανεπιστήμιο Κύπρου
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**γ.** Άοσμος ☐☐☐☐☐ Μυρίζει έντονα *

**δ. Κίνηση αέρα** Στάσιμος ☐☐☐☐☐ Με πολλά ρεύματα *

**ε. Γενική αξιολόγηση για την ποιότητα του εσωτερικού αέρα της αίθουσας** *Θα εξηγηθεί προφορικά

Πολύ ικανοποιητική ☐☐☐☐☐ Απαράδεκτη

**Δ. ΟΠΤΙΚΗ ΑΝΕΣΗ**

**Πώς αξιολογείτε την ΟΠΤΙΚΗ ΑΝΕΣΗ του κτιρίου;**

**α. Φωτισμός** Πολύ σκοτεινά ☐☐☐☐☐☐☐ Πολύ φωτεινά

**β.** Ομοιόμορφος ☐☐☐☐☐☐☐ Ανόμοιος

**γ.** Δεν προξενεί θαμπωμα ☐☐☐☐☐☐☐ Προξενεί θάμπωμα

**δ.** Πολύ ικανοποιητικός ☐☐☐☐☐☐☐ Απαράδεκτος

**Ε. ΣΥΝΘΗΚΕΣ ΛΕΙΤΟΥΡΓΙΑΣ ΚΤΙΡΙΟΥ**

**1. ΣΥΝΗΘΕΙΕΣ ΑΝΟΙΓΜΑΤΩΝ ΠΑΡΑΘΥΡΩΝ**

**α. Πότε ανοίγετε τους φεγγίτες (ψηλά παράθυρά);**

Ποτέ ☐ Κάποτε ☐ Συχνά ☐

**β. Πότε είναι ΑΝΟΙΚΤΑ τα κύρια ΠΑΡΑΘΥΡΑ;**

Σημειώστε Χ όπου εφαρμόζεται:

**ΧΕΙΜΩΝΑ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**ΑΝΟΙΞΗ/ ΦΘΙΝΟΠΩΡΟ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**ΚΑΛΟΚΑΙΡΙ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

Πανεπιστήμιο Κύπρου
Τμήμα Αρχιτεκτονικής

ΕΡΩΤΗΜΑΤΟΛΟΓΙΟ

**2. ΣΥΝΗΘΕΙΕΣ ΕΦΑΡΜΟΓΗΣ ΚΟΥΡΤΙΝΩΝ**

Πότε **ΚΛΕΙΝΕΤΕ** τις **ΚΟΥΡΤΙΝΕΣ**;
Σημειώστε Χ όπου εφαρμόζεται:

**ΧΕΙΜΩΝΑ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**ΑΝΟΙΞΗ/ ΦΘΙΝΟΠΩΡΟ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**ΚΑΛΟΚΑΙΡΙ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**3. ΣΥΝΗΘΕΙΕΣ ΕΦΑΡΜΟΓΗΣ ΤΕΧΝΗΤΟΥ ΦΩΤΙΣΜΟΥ**

Πότε **ΑΝΟΙΓΕΤΕ** τα **ΦΩΤΑ**;
Σημειώστε Χ όπου εφαρμόζεται:

**ΧΕΙΜΩΝΑ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**ΑΝΟΙΞΗ/ ΦΘΙΝΟΠΩΡΟ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**ΚΑΛΟΚΑΙΡΙ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**4. ΣΥΝΗΘΕΙΕΣ ΕΦΑΡΜΟΓΗΣ ΑΝΕΜΙΣΤΗΡΑ**

Η τάξη σας έχει ΑΝΕΜΙΣΤΗΡΑ; Ναι [ ] Όχι [ ]

**Αν ναι, πότε εφαρμόζεται;**

**ΑΝΟΙΞΗ/ ΦΘΙΝΟΠΩΡΟ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

**ΚΑΛΟΚΑΙΡΙ**

| | |
|---|---|
| 1-2η περίοδος | |
| **1ο διάλλειμα** | |
| 3-4η περίοδος | |
| **2ο διάλλειμα** | |
| 5-6η περίοδος | |
| **3ο διάλλειμα** | |
| 7η περίοδος | |
| 8η περίοδος | |

Πανεπιστήμιο Κύπρου
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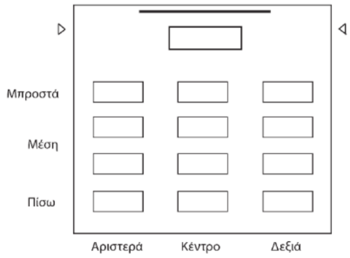
ΕΡΩΤΗΜΑΤΟΛΟΓΙΟ

**Ζ. ΑΠΟΣΤΑΣΗ ΑΠΟ ΤΑ ΠΑΡΑΘΥΡΑ**

**Σε ποια θέση βρίσκομαι μέσα στην τάξη:**




| | | | | | | |
|---|---|---|---|---|---|---|
| **(α)** | Αριστερά | ☐ | Κέντρο | ☐ | Δεξιά | ☐ |
| **(β)** | Μπροστά | ☐ | Μέση | ☐ | Πίσω | ☐ |

**Σας ευχαριστούμε για τη συνεργασία.**

## Appendix F: Observer form

**ΕΝΤΥΠΟ ΠΑΡΑΤΗΡΗΣΗΣ ΑΠΟ ΕΡΕΥΝΗΤΗ**

Σχολείο: ............................................................................................................................................................

Ημερομηνία:.......................................................................................................................................................

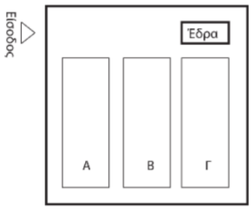
Ώρα: ...................................................................................................................................................................

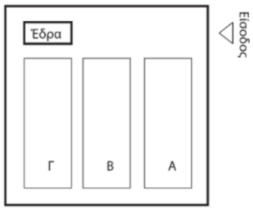
Περίοδος:............................................................................................................................................................

Τάξη:...................................................................................................................................................................

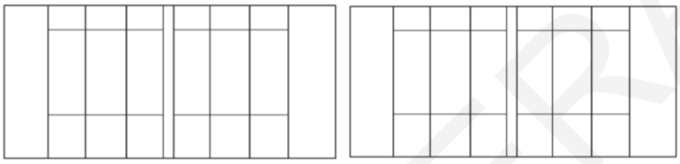
Μάθημα προηγούμενη περιόδου:.......................................................................................................................

Προσανατολισμός εισόδου αίθουσας:...............................................................................................................

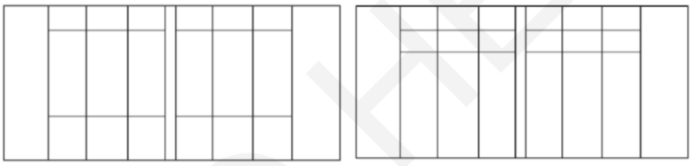
(A) 


(B) 


Περιγραφή ανοιγμάτων αίθουσας:......................................................................................................................

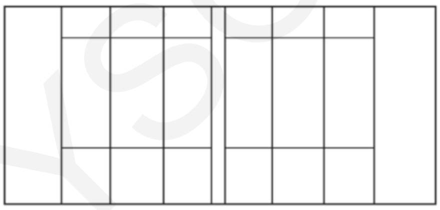


(α)

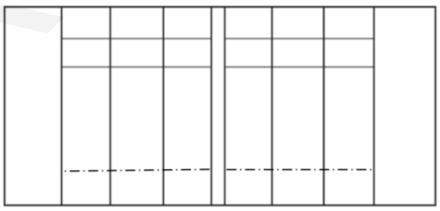


(β)

Περιγραφή κατάστασης ανοιγμάτων:..................................................................................................................



κύρια όψη



απέναντι όψη

# Appendix G: Categorization of educational buildings in Cyprus

| Α/Α | Κωδ. | Όνομα σχολείου: | Βαθμίδα σχολείου: Α. Προδημοτική Εκπαίδευση Β. Δημοτική Εκπαίδευση Γ. Μέση Γενική Εκπαίδευση (Γ1: Γυμνάσιο, Γ2: Λύκειο) Δ. Μέση Τεχνική και Επαγγελματική Εκπαίδευση | Επαρχία Σχολείου: Α. Λευκωσία Β. Λάρνακα Γ. Λεμεσός Δ. Αμμοχώστος Ε. Πάφος | Πόλη/Χωριό Δήμος/ Κοινότητα | Μέγεθος σχολείου και αρχιτεκτονικά χαρακτηριστικά | | | | | | | | Ενεργειακή αναβάθμιση: | | Αντισεισμική αναβάθμιση | Καλοκαιρινό ωράριο |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Αρ. Μαθητών: | Χώροι αιθ. Διδασκαλίας | Χώροι διοίκησης | Εργαστ. | Ειδικές αίθουσες | | Σχεδιαστήρια | Αιθ. Πολ. | Ναι Όχι | Αν ναι, χρονολογία (ισχύει | Ναι/Όχι | |
| | | | | | | | | | | Μαθημάτων | Στήριξης | | | | | | |
| 1 | N1 | Νηπ. Αγίας Μαρίνας | A | A | Δήμος Στροβόλου | 43 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 2 | N2 | Νηπ. Αγίου Ανδρέα | A | A | Δήμος Λευκωσίας | 42 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 3 | N3 | Νηπ. Αγίου Αντωνίου | A | A | Δήμος Λευκωσίας | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 4 | N4 | Νηπ. Αγίου Βασιλείου "Λοϊζίδειο" | A | A | Δήμος Στροβόλου | 70 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 5 | N5 | Νηπ. Αγίου Δημητρίου | A | A | Δήμος Στροβόλου | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 6 | N6 | Νηπ. Αγίου Δομετίου Α΄ | A | A | Δήμος Αγίου Δομετίου | 46 | 2 | | | | | | | Ναι | 16/10/24 | Ναι | Οχι |
| 7 | N7 | Νηπ. Αγίου Δομετίου Β΄ | A | A | Δήμος Αγίου Δομετίου | 38 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 8 | N8 | Νηπ. Αγίου Δομετίου Γ΄ | A | A | Δήμος Αγίου Δομετίου | 22 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 9 | N9 | Νηπ. Αγίου Κασσιανού | A | A | Δήμος Λευκωσίας | 19 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 10 | N10 | Νηπ. Αγίου Σπυρίδωνα | A | A | Δήμος Στροβόλου | 30 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 11 | N11 | Νηπ. Αγλαντζιάς Α΄ | A | A | Δήμος Αγλατζιάς | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 12 | N12 | Νηπ. Αγλαντζιάς Δ΄ | A | A | Δήμος Αγλατζιάς | 69 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 13 | N13 | Νηπ. Αγλαντζιάς Ε΄ | A | A | Δήμος Αγλατζιάς | 66 | 3 | | | | | | | Οχι | | Ναι | Ναι |
| 14 | N14 | Νηπ. Αγλαντζιάς Στ΄ | A | A | Δήμος Αγλατζιάς | 91 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 15 | N15 | Νηπ. Ακρόπολης | A | A | Δήμος Στροβόλου | 42 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 16 | N16 | Νηπ. Αποστόλου Βαρνάβα | A | A | Δήμος Στροβόλου | 42 | 2 | | | | | | | Ναι | 12/11/24 | Ναι | Οχι |
| 17 | N17 | Νηπ. Αποστόλου Λουκά | A | A | Δήμος Στροβόλου | 41 | 2 | | | | | | | Οχι | | Ναι | Ναι |
| 18 | N18 | Νηπ. Αρχαγγέλου | A | A | Δήμος Στροβόλου | 30 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 19 | N19 | Νηπ. Δασούπολης | A | A | Δήμος Στροβόλου | 73 | 3 | | | | | | | Ναι | 19/10/24 | Ναι | Οχι |
| 20 | N20 | Νηπ. Έγκωμης Α΄ | A | A | Δήμος Έγκωμης | 41 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 21 | N21 | Νηπ. Έγκωμης Β΄ | A | A | Δήμος Έγκωμης | 43 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 22 | N22 | Νηπ. Ελένειο | A | A | Δήμος Λευκωσίας | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 23 | N23 | Νηπ. Εξόρμησης Στροβόλου | A | A | Δήμος Στροβόλου | 21 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 24 | N24 | Νηπ. Καϊμακλίου | A | A | Δήμος Λευκωσίας | 71 | 3 | | | | | | | Οχι | | Οχι | Οχι |
| 25 | N25 | Νηπ. Καϊμακλίου Γ΄ | A | A | Δήμος Λευκωσίας | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 26 | N26 | Νηπ. Κοινωνικής Μέριμνας Αγίων Ομολογητών | A | A | Δήμος Στροβόλου | 67 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 27 | N27 | Νηπ. Αγίων Ομολογητών (ΝΕΟ) | A | A | Δήμος Λευκωσίας | 22 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 28 | N28 | Νηπ. Κοινωνικής Μέριμνας Αγίων Ομολογητών Στρόβολος ΙΙΙ | A | A | Δήμος Στροβόλου | 23 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 29 | N29 | Νηπ. Κωνσταντινουπόλεως | A | A | Δήμος Στροβόλου | 43 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 30 | N30 | Νηπ. Μακεδονίτισσας Α΄ | A | A | Δήμος Έγκωμης | 54 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 31 | N31 | Νηπ. Μακεδονίτισσας Β΄ | A | A | Δήμος Έγκωμης | 50 | 2 | | | | | | | Ναι | 20/10/24 | Ναι | Οχι |
| 32 | N32 | Νηπ. Μακεδονίτισσας Γ΄ - Στυλιανού Λένα | A | A | Δήμος Έγκωμης | 72 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 33 | N33 | Νηπ. Μάνα | A | A | Δήμος Λευκωσίας | 86 | 5 | | | | | | | Οχι | | Ναι | Οχι |
| 34 | N34 | Νηπ. Νοσοκομείου Μακαρείου | A | A | Δήμος Στροβόλου | 0 | 1 | | | | | | | Οχι | | Ναι | Ναι |
| 35 | N35 | Νηπ. Παιδομάνα | A | A | Δήμος Λευκωσίας | 13 | 1 | | | | | | | Οχι | | Ναι | Οχι |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 36 | N36 | Νηπ. Παλουριώτισσας Α΄ | Α | Α | Δήμος Λευκωσίας | 22 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 37 | N37 | Νηπ. Παλουριώτισσας Β΄ | Α | Α | Δήμος Λευκωσίας | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 38 | N38 | Νηπ. ΠΑΣΥΔΥ Αγλαντζιάς | Α | Α | Δήμος Αγλατζιάς | 22 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 39 | N39 | Νηπ. ΠΑΣΥΔΥ Λευκωσίας | Α | Α | Δήμος Λευκωσίας | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 40 | N40 | Νηπ. Περνέρα | Α | Α | Δήμος Στροβόλου | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 41 | N41 | Νηπ. Πεύκιος Γεωργιάδης | Α | Α | Δήμος Στροβόλου | 44 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 42 | N42 | Νηπ. Σταυρού | Α | Α | Δήμος Στροβόλου | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 43 | N43 | Νηπ. Φανερωμένης | Α | Α | Δήμος Λευκωσίας | 20 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 44 | N44 | Νηπ. Χ΄΄Γεωργάκη Κορνέσιου | Α | Α | Δήμος Λευκωσίας | 23 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 45 | N45 | Νηπ. Χρυσελεούσας | Α | Α | Δήμος Στροβόλου | 44 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 46 | N46 | Νηπ. Αγίας Βαρβάρας | Α | Α | Αγία Βαρβάρα | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 47 | N47 | Νηπ. Παπασταύρου Παπαγαθαγγέλου | Α | Α | Αγία Βαρβάρα | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 48 | N48 | Νηπ. Αγίου Μάρωνα | Α | Α | Δήμος Λακατάμειας | 14 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 49 | N49 | Νηπ. Ανθούπολης | Α | Α | Δήμος Λακατάμειας | 77 | 5 | | | | | | | Οχι | | Ναι | Οχι |
| 50 | N50 | Νηπ. Γερίου Α΄ | Α | Α | Δήμος Γερίου | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 51 | N51 | Νηπ. Γερίου Β' | Α | Α | Δήμος Γερίου | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 52 | N52 | Νηπ. Δαλιού Α΄- Αντρέας Παναγίδης | Α | Α | Δήμος Ιδαλίου | 71 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 53 | N53 | Νηπ. Δαλιού Β΄ | Α | Α | Δήμος Ιδαλίου | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 54 | N54 | Νηπ. Δαλιού Γ΄- Αγίων Κωνσταντίνου και Ελένης | Α | Α | Δήμος Ιδαλίου | 98 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 55 | N55 | Νηπ. Λακατάμειας Δ΄ - Αγίου Νεοφύτου | Α | Α | Δήμος Λακατάμειας | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 56 | N56 | Νηπ. Λακατάμειας Ε' - Αγίου Ιωάννη Χρυσοστόμου | Α | Α | Δήμος Λακατάμειας | 74 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 57 | N57 | Νηπ. Λακατάμειας Α΄ | Α | Α | Δήμος Λακατάμειας | 99 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 58 | N58 | Νηπ. Λακατάμειας Στ΄ | Α | Α | Δήμος Λακατάμειας | 69 | 3 | | | | | | | Ναι | 03/11/24 | Ναι | Οχι |
| 59 | N59 | Νηπ. Λακατάμειας Β΄ - Αγίου Μάμα | Α | Α | Δήμος Λακατάμειας | 61 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 60 | N60 | Νηπ. Λακατάμειας Ζ΄- Αγίου Παντελεήμονα | Α | Α | Δήμος Λακατάμειας | 44 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 61 | N61 | Νηπ. Λατσιών Α΄ | Α | Α | Δήμος Λατσιών | 69 | 3 | | | | | | | Ναι | 08/05/26 | Ναι | Οχι |
| 62 | N62 | Νηπ. Λατσιών Β΄ | Α | Α | Δήμος Λατσιών | 73 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 63 | N63 | Νηπ. Λατσιών Γ΄ | Α | Α | Δήμος Λατσιών | 45 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 64 | N64 | Νηπ. Λατσιών Δ΄ | Α | Α | Δήμος Λατσιών | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 65 | N65 | Νηπ. Παλαιομετόχου Α΄ | Α | Α | Παλιομέτοχο | 43 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 66 | N66 | Νηπ. Παλαιομετόχου Β΄ | Α | Α | Παλιομέτοχο | 18 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 67 | N67 | Νηπ. Πέρα Χωρίου Νήσου Α΄ | Α | Α | Πέρα Χωριό Νήσου | 46 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 68 | N68 | Νηπ. Πέρα Χωρίου Νήσου Β΄ | Α | Α | Πέρα Χωριό Νήσου | 22 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 69 | N69 | Νηπ. Αγ. Επιφανίου | Α | Α | Αγ. Επιφάνειος | 8 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 70 | N70 | Νηπ. Άγιος Ιωάννης Λευκωσία | Α | Α | Αγ. Ιωάννης Μαλούντας | 13 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 71 | N71 | Νηπ. Αγίας Μαρίνας Ξυλιάτου | Α | Α | Αγ. Μαρίνα Ξυλιάτου | 7 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 72 | N72 | Νηπ. Αγίων Τριμιθιάς | Α | Α | Αγ. Τριμιθιάς | 44 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 73 | N73 | Νηπ. Ακακίου | Α | Α | Ακάκι – Δένεια | 67 | 3 | | | | | | | Ναι | 15/09/24 | Ναι | Οχι |
| 74 | N74 | Νηπ. Αλάμπρας | Α | Α | Αλάμπρα | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 75 | N75 | Νηπ. Ανάγειας | Α | Α | Ανάγυια | 21 | 1 | | | | | | | Οχι | | Οχι | Οχι |
| 76 | N76 | Νηπ. Αρεδιού | Α | Α | Αρεδιού | 25 | 1 | | | | | | | Οχι | | Οχι | Οχι |
| 77 | N77 | Νηπ. Ασίνου | Α | Α | Ασίνου | 25 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 78 | N78 | Νηπ. Αστρομερίτη | Α | Α | Αστρομερίτης | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 79 | N79 | Νηπ. Δευτεράς Πάνω | Α | Α | Δευτερά | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 80 | N80 | Νηπ. Εργατών | Α | Α | Εργάτες | 20 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 81 | N81 | Νηπ. Ευρύχου | Α | Α | Ευρύχου | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 82 | N82 | Νηπ. Κακοπετριάς | Α | Α | Κακοπετριά | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 83 | N83 | Νηπ. Καλού Χωριού Ορεινής | Α | Α | Καλό Χωριό Κλήρου - Ορεινής | 16 | 1 | | | | | | | Οχι | | Οχι | Οχι |
| 84 | N84 | Νηπ. Καμπιών | Α | Α | Καμπιά - Αναλυόντας | 15 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 85 | N85 | Νηπ. Κάμπου | Α | Α | Κάμπος | 1 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 86 | N86 | Νηπ. Καπέδων | Α | Α | Καπέδες | 23 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 87 | N87 | Νηπ. Κάτω Πύργος | Α | Α | Κάτω Πύργος Λ/σίας | 6 | 1 | | | | | | | Οχι | | Ναι | Οχι |

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| 88 | N88 | Νηπ. Κλήρου | A | A | Κλήρου | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 89 | N89 | Νηπ. Κοκκινοτριμιθιάς | A | A | Κοκκινοτριμιθιά | 61 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 90 | N90 | Νηπ. Κοράκου | A | A | Κοράκου | 21 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 91 | N91 | Νηπ. Λυθροδόντα | A | A | Λυθροδόντας | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 92 | N92 | Νηπ. Λυμπιών | A | A | Λύμπια | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 93 | N93 | Νηπ. Μαθιάτη | A | A | Μαθιάτης | 23 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 94 | N94 | Νηπ. Μάμμαρη | A | A | Μάμμαρι | 44 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 95 | N95 | Νηπ. Μενίκου | A | A | Μένοικο | 19 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 96 | N96 | Νηπ. Μιτσερού - Κουρέλλειο | A | A | Μιτσερό | 21 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 97 | N97 | Νηπ. Μουτουλλά | A | A | Μουτουλλάς | 3 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 98 | N98 | Νηπ. Ορούντας | A | A | Ορούντα (Κάτω Μονή) | 7 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 99 | N99 | Νηπ. Παλαιχωρίου | A | A | Παλαιχώρι | 24 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 100 | N100 | Νηπ. Περιστερώνα | A | A | Περιστερώνα | 41 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 101 | N101 | Νηπ. Ποταμιάς | A | A | Ποταμιά | 19 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 102 | N102 | Νηπ. Ριζοκάρπασο | A | A | Ριζοκάρπασο | 14 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 103 | N103 | Νηπ. Σιας | A | A | Σιά | 20 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 104 | N104 | Νηπ. Ταμασού | A | A | Ταμασού | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 105 | N105 | Νηπ. Τεμβριάς | A | A | Τεμπριά | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 106 | N106 | Νηπ. Τσερίου | A | A | Δήμος Τσερίου | 67 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 107 | N107 | Νηπ. Φαρμακά-Καμπιού | A | A | Φαρμακάς - Καμπιά | 10 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 108 | N108 | Νηπ. Ψιμολόφου | A | A | Ψιμολόφου | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 109 | N109 | Νηπ Αγίων Ανάργυρων | A | B | Δήμος Λάρνακας | 45 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 110 | N110 | Νηπ. Αγίου Γεωργίου | A | B | Δήμος Λάρνακας | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 111 | N111 | Νηπ. Αγίου Ιωάννη | A | B | Δήμος Λάρνακας | 43 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 112 | N112 | Νηπ. Αγίου Λαζάρου Α΄ | A | B | Δήμος Λάρνακας | 21 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 113 | N113 | Νηπ. Αγίου Λαζάρου Β΄ | A | B | Δήμος Λάρνακας | 35 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 114 | N114 | Νηπ. Αραδίππου Ε΄ - Αγίων Αυξεντίου και Ευσταθίου | A | B | Δήμος Αραδίππου | 69 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 115 | N115 | Νηπ. Δροσιάς | A | B | Δήμος Λάρνακας | 71 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 116 | N116 | Νηπ. Καμάρων | A | B | Δήμος Λάρνακας | 45 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 117 | N117 | Νηπ. Εθνάρχη Μακάριου - Τσιακκιλερό | A | B | Δήμος Λάρνακας | 14 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 118 | N118 | Νηπ. Εθνάρχη Μακάριου - Κόκκινες | A | B | Δήμος Λάρνακας | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 119 | N119 | Νηπ. Ζήνων | A | B | Δήμος Λάρνακας | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 120 | N120 | Νηπ. Καθαρής - Δημήτρη Λιπέρτη | A | B | Δήμος Λάρνακας | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 121 | N121 | Νηπ. Καλογερά | A | B | Δήμος Λάρνακας | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 122 | N122 | Νηπ. Παυλίδειο | A | B | Δήμος Λάρνακας | 33 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 123 | N123 | Νηπ. Πρόδρομου - Φλωρίδειο | A | B | Δήμος Λάρνακας | 63 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 124 | N124 | Νηπ. Σωτήρος | A | B | Δήμος Λάρνακας | 37 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 125 | N125 | Νηπ. Αραδίππου Α΄ | A | B | Δήμος Αραδίππου | 99 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 126 | N126 | Νηπ. Αραδίππου Β΄ | A | B | Δήμος Αραδίππου | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 127 | N127 | Νηπ. Αραδίππου Γ΄ | A | B | Δήμος Αραδίππου | 50 | 2 | | | | | | | Ναι | 05/10/24 | Ναι | Οχι |
| 128 | N128 | Νηπ. Αραδίππου Δ΄ - Αγίου Φανουρίου | A | B | Δήμος Αραδίππου | 74 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 129 | N129 | Νηπ. Λιβαδιών Α΄ | A | B | Δήμος Λειβαδιών | 72 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 130 | N130 | Νηπ. Λιβαδιών Β΄ | A | B | Δήμος Λειβαδιών | 50 | 2 | | | | | | | Ναι | 17/11/24 | Ναι | Οχι |
| 131 | N131 | Νηπ. Ξυλοτύμβου Α΄ | A | B | Ξυλοτύμβου | 45 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 132 | N132 | Νηπ. Ξυλοτύμβου Β΄ | A | B | Ξυλοτύμβου | 22 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 133 | N133 | Νηπ. Ορμίδειας Α΄ | A | B | Ορμήδεια | 42 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 134 | N134 | Νηπ. Ορμίδειας Β΄ | A | B | Ορμήδεια | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 135 | N135 | Νηπ. Αγγλισίδων | A | B | Αγγλισίδες | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 136 | N136 | Νηπ. Αγίου Θεοδώρου | A | B | Άγιος Θεόδωρος Λ/κας | 18 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 137 | N137 | Νηπ. Αθηένου | A | B | Δήμος Αθηένου | 68 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 138 | N138 | Νηπ. Αλεθρικού | A | B | Αλεθρικό | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 139 | N139 | Νηπ. Αναφωτίδας | A | B | Αναφωτία | 23 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 140 | N140 | Νηπ. Δρομολαξιάς | A | B | Δρομολαξιά | 63 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 141 | N141 | Νηπ. Ζυγίου | A | B | Ζύγι | 12 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 142 | N142 | Νηπ. Καλαβασού | A | B | Καλαβασός | 14 | 1 | | | | | | | Οχι | | Οχι | Οχι |
| 143 | N143 | Νηπ. Καλού Χωριού | A | B | Καλό Χωριό Λ/κας | 35 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 144 | N144 | Νηπ. Κιτίου | A | B | Κίτι | 75 | 3 | | | | | | | Ναι | 10/05/26 | Οχι | Οχι |
| 145 | N145 | Νηπ. Κόρνου | A | B | Κόρνος | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 146 | N146 | Νηπ. Κοφίνου | A | B | Κοφίνου | 35 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 147 | N147 | Νηπ. Λεύκαρα Πάνω | A | B | Δήμος Πάνω Λευκάρων | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 148 | N148 | Νηπ. Μαζωτού | A | B | Μαζωτός | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 149 | N149 | Νηπ. Μαρωνίου | A | B | Μαρώνι | 21 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 150 | N150 | Νηπ. Μενεού | A | B | Δρομολαξιά | 49 | 2 | | | | | | | Ναι | 06/05/25 | Ναι | Οχι |
| 151 | N151 | Νηπ. Μοσφιλωτής | A | B | Μοσφιλωτή | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |

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| 152 | N152 | Νηπ. Ξυλοφάγου | Α | Β | Ξυλοφάγου | 40 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 153 | N153 | Νηπ. Βορόκληνης | Α | Β | Βορόκληνη | 74 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 154 | N154 | Νηπ. Περιβολιών | Α | Β | Περιβόλια | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 155 | N155 | Νηπ. Πύλας | Α | Β | Πύλα | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 156 | N156 | Νηπ. Πυργών | Α | Β | Πυργά | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 157 | N157 | Νηπ. Τερσεφάνου | Α | Β | Τερσεφάνου | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 158 | N158 | Νηπ. Τόχνης | Α | Β | Τόχνη | 15 | 1 | | | | | | | Οχι | | Οχι | Οχι |
| 159 | N159 | Νηπ. Τρούλλων | Α | Β | Τρούλλοι | 36 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 160 | N160 | Νηπ. Χοιροκοιτίας | Α | Β | Χοιροκοιτία | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 161 | N161 | Νηπ. Ψευδά | Α | Β | Ψευδάς | 31 | 2 | | | | | | | Ναι | 09/10/29 | Ναι | Οχι |
| 162 | N162 | Νηπ. Αυγόρου Α΄ | Α | Δ | Αυγόρου | 43 | 2 | | | | | | | Ναι | 06/05/25 | Ναι | Οχι |
| 163 | N163 | Νηπ. Αυγόρου Β΄ | Α | Δ | Αυγόρου | 38 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 164 | N164 | Νηπ. Δερύνειας | Α | Δ | Δερύνεια | 70 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 165 | N165 | Νηπ. Παραλιμνίου - Γιώρκειο | Α | Δ | Δήμος Παραλιμνίου | 43 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 166 | N166 | Νηπ. Παραλιμνίου Α΄ | Α | Δ | Δήμος Παραλιμνίου | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 167 | N167 | Νηπ. Παραλιμνίου Β΄ | Α | Δ | Δήμος Παραλιμνίου | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 168 | N168 | Νηπ. Παραλιμνίου Γ΄ | Α | Δ | Δήμος Παραλιμνίου | 44 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 169 | N169 | Νηπ. Παραλιμνίου Δ΄ | Α | Δ | Δήμος Παραλιμνίου | 41 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 170 | N170 | Νηπ. Αγίας Νάπας | Α | Δ | Αγία Νάπα | 65 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 171 | N171 | Νηπ. Βρυσούλων | Α | Δ | Βρυσούλλες | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 172 | N172 | Νηπ. Δάσους Άχνας - Φώτης Πίττας | Α | Δ | Δασάκι Άχνας | 50 | 2 | | | | | | | Ναι | 11/05/26 | Ναι | Οχι |
| 173 | N173 | Νηπ. Λιοπετρίου | Α | Δ | Λιοπέτρι | 64 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 174 | N174 | Νηπ. Σωτήρας | Α | Δ | Σωτήρα | 97 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 175 | N175 | Νηπ. Φρενάρους | Α | Δ | Φρέναρος (Κοκκινοχώρια) | 55 | 3 | | | | | | | Ναι | 28/03/29 | Ναι | Οχι |
| 176 | N176 | Νηπ. Δερύνειας Γ΄ | Α | Δ | Δερύνεια | 38 | 2 | | | | | | | Ναι | 07/10/24 | Ναι | Οχι |
| 177 | N177 | Νηπ. Δερύνειας Β΄ | Α | Δ | Δερύνεια | 70 | | | | | | | | Ναι | 12/04/28 | Ναι | Οχι |
| 178 | N178 | Νηπ. Λεμεσού Α΄ | Α | Γ | Δήμος Λεμεσού | 20 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 179 | N179 | Νηπ. Λεμεσού Β΄ | Α | Γ | Δήμος Λεμεσού | 52 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 180 | N180 | Νηπ. Λεμεσού Γ΄ | Α | Γ | Δήμος Λεμεσού | 42 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 181 | N181 | Νηπ. Λεμεσού Δ΄ - "Λητώ Παπαχριστοφόρου" | Α | Γ | Δήμος Λεμεσού | 75 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 182 | N182 | Νηπ. Λεμεσού Ε΄- Αγίου Ιωάννη | Α | Γ | Δήμος Λεμεσού | 72 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 183 | N183 | Νηπ. Λεμεσού Στ΄ - Αγίου Νικολάου | Α | Γ | Δήμος Λεμεσού | 59 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 184 | N184 | Νηπ. Λεμεσού Ζ΄ - Αποστόλου Αντρέα | Α | Γ | Δήμος Λεμεσού | 75 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 185 | N185 | Νηπ. Λεμεσού Η΄ - Ομονοίας | Α | Γ | Δήμος Λεμεσού | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 186 | N186 | Νηπ. Αγίας Μαρίνας Καψάλου | Α | Γ | Δήμος Λεμεσού | 75 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 187 | N187 | Νηπ. Λεμεσού Θ΄ - Καψάλου | Α | Γ | Δήμος Λεμεσού | 50 | 2 | | | | | | | Ναι | 15/09/24 | Ναι | Οχι |
| 188 | N188 | Νηπ. Λεμεσού Ι΄ - Χαλκούτσας | Α | Γ | Δήμος Λεμεσού | 73 | 3 | | | | | | | Ναι | 02/06/21 | Ναι | Οχι |
| 189 | N189 | Νηπ. Λεμεσού ΙΓ΄ - Αγίου Σπυρίδωνα Α' | Α | Γ | Δήμος Λεμεσού | 70 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 190 | N190 | Νηπ. Λεμεσού ΙΣτ΄ - Ζακακίου | Α | Γ | Δήμος Λεμεσού | 72 | 3 | | | | | | | Ναι | 24/10/28 | Ναι | Οχι |
| 191 | N191 | Νηπ. Λεμεσού ΙΗ΄ - Αγίου Αντωνίου | Α | Γ | Δήμος Λεμεσού | 45 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 192 | N192 | Νηπ. Λεμεσού ΙΘ΄ - Αγίας Φυλάξεως | Α | Γ | Δήμος Λεμεσού | 70 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 193 | N193 | Νηπ. Λεμεσού Κ΄ - Αγίου Παντελεήμονα | Α | Γ | Δήμος Λεμεσού | 45 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 194 | N194 | Νηπ. Λεμεσού ΚΑ΄ - Κοντοβάθεια | Α | Γ | Δήμος Λεμεσού | 73 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 195 | N195 | Νηπ. Λεμεσού ΚΒ΄ - Αγίου Γεωργίου | Α | Γ | Δήμος Λεμεσού | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 196 | N196 | Νηπ. Λεμεσός ΚΓ΄ - Αγίου Σπυρίδωνα Β΄ | Α | Γ | Δήμος Λεμεσού | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 197 | N197 | Νηπ. Λεμεσού ΚΕ΄ - Εκάλης | Α | Γ | Δήμος Λεμεσού | 74 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 198 | N198 | Νηπ. Λεμεσού ΚΣτ΄ - Παναγίας Τριχερούσας | Α | Γ | Δήμος Λεμεσού | 74 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 199 | N199 | Νηπ. Λεμεσού ΚΖ΄ - Τιμίου Προδρόμου | Α | Γ | Δήμος Λεμεσού | 73 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 200 | N200 | Νηπ. Λεμεσού Μέσα Γειτονιά ΚΘ΄ - Γ.Ν. Καλογερόπουλου | Α | Γ | Δήμος Λεμεσού | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 201 | N201 | Νηπ. Κολοσσίου Α΄- Αποστόλου Λουκά | Α | Γ | Κολόσσι | 48 | 2 | | | | | | | Ναι | 05/10/24 | Ναι | Οχι |
| 202 | N202 | Νηπ. Κολοσσίου Β΄- Αποστόλου Ανδρέα και Αγίας Φωτεινής | Α | Γ | Κολόσσι | 48 | 2 | | | | | | | Ναι | 09/05/26 | Ναι | Οχι |

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| 203 | N203 | Νηπ. Κάτω Πολεμιδιών Α΄ - Παναγίας Ευαγγελίστριας | Α | Γ | Δήμος Κάτω Πολεμιδιών | 44 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 204 | N204 | Νηπ. Κάτω Πολεμιδιών Β΄ - Αγίου Γεωργίου | Α | Γ | Δήμος Κάτω Πολεμιδιών | 48 | 2 | | | | | | | Ναι | 24/09/24 | Ναι | Οχι |
| 205 | N205 | Νηπ. Κάτω Πολεμιδιών Γ΄ - Αγίου Νικολάου | Α | Γ | Δήμος Κάτω Πολεμιδιών | 72 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 206 | N206 | Νηπ. Κάτω Πολεμιδιών ΚΗ΄ - Αρχαγγέλου Μιχαήλ | Α | Γ | Δήμος Κάτω Πολεμιδιών | 46 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 207 | N207 | Νηπ. Ποταμού Γερμασόγειας Α΄ | Α | Γ | Δήμος Γερμασόγειας | 42 | 2 | | | | | | | Οχι | | Οχι | Οχι |
| 208 | N208 | Νηπ. Ποταμού Γερμασόγειας Β΄ | Α | Γ | Δήμος Γερμασόγειας | 72 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 209 | N209 | Νηπ. Ύψωνα Β' | Α | Γ | Δήμος Ύψωνα | 93 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 210 | N210 | Νηπ. Ύψωνα Γ΄ | Α | Γ | Δήμος Ύψωνα | 63 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 211 | N211 | Νηπ. Αγίων Αναργύρων | Α | Γ | Αγ. Ανάργυροι Λ/σού (Μονή - Μοναγρούλι) | 20 | 1 | | | | | | | Ναι | 18/11/24 | Ναι | Οχι |
| 212 | N212 | Νηπ. Αγίου Αθανασίου | Α | Γ | Δήμος Αγίου Αθανασίου | 118 | 5 | | | | | | | Οχι | | Ναι | Οχι |
| 213 | N213 | Νηπ. Αγίου Τύχωνα | Α | Γ | Άγιος Τύχωνας | 21 | 1 | | | | | | | Ναι | 15/09/24 | Ναι | Οχι |
| 214 | N214 | Νηπ. Αγρού | Α | Γ | Αγρός | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 215 | N215 | Νηπ. Ακρωτηρίου | Α | Γ | Ακρωτήρι | 23 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 216 | N216 | Νηπ. Ασγάτας | Α | Γ | Ασγάτα | 12 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 217 | N217 | Νηπ. Αυδήμου (Περιφερειακό) | Α | Γ | Αυδήμου | 21 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 218 | N218 | Νηπ. Γερμασόγειας | Α | Γ | Δήμος Γερμασόγειας | 68 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 219 | N219 | Νηπ. Επισκοπής | Α | Γ | Επισκοπή Λ/σού | 73 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 220 | N220 | Νηπ. Ερήμης | Α | Γ | Ερήμη | 45 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 221 | N221 | Νηπ. Ιαματική | Α | Γ | Ιαματική (Επταγώνι) | 22 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 222 | N222 | Νηπ. Καλού Χωριού | Α | Γ | Καλό Χωριό Λ/σου | 18 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 223 | N223 | Νηπ. Καντού | Α | Γ | Καντού | 19 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 224 | N224 | Νηπ. Κιβίδων Πάνω | Α | Γ | Κιβίδες | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 225 | N225 | Νηπ. Κυπερούντας | Α | Γ | Κυπερούντα | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 226 | N226 | Νηπ. Λινόπετρας | Α | Γ | Δήμος Αγίου Αθανασίου | 64 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 227 | N227 | Νηπ. Μουτταγιάκας | Α | Γ | Μουτταγιάκα | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 228 | N228 | Νηπ. Παλώδειας | Α | Γ | Παλώδια | 39 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 229 | N229 | Νηπ. Παρεκκλησιάς | Α | Γ | Παρεκκλησιά | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 230 | N230 | Νηπ. Πάχνας | Α | Γ | Πάχνα | 18 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 231 | N231 | Νηπ. Πελενδριού | Α | Γ | Πελένδρι | 19 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 232 | N232 | Νηπ. Πεντακώμου | Α | Γ | Πεντάκωμο | 9 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 233 | N233 | Νηπ. Πισσουρίου | Α | Γ | Πισσούρι | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 234 | N234 | Νηπ. Πλατρών Πάνω | Α | Γ | Πλάτρες | 12 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 235 | N235 | Νηπ. Πάνω Πολεμιδιών-Καρμιώτισσας | Α | Γ | Πολεμίδια Πάνω-Καρμιώτισσα | 93 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 236 | N236 | Νηπ. Πύργου | Α | Γ | Πύργος Λεμεσού | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 237 | N237 | Νηπ. Σπιταλίου-Παραμύθας | Α | Γ | Σπιτάλι | 23 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 238 | N238 | Νηπ. Τραχωνίου | Α | Γ | Τραχώνι | 72 | 3 | | | | | | | Ναι | 19/10/24 | Ναι | Οχι |
| 239 | N239 | Νηπ. Τραχωνίου Β' | Α | Γ | Τραχώνι | | | | | | | | | Ναι | 28/03/29 | Ναι | Οχι |
| 240 | N240 | Νηπ. Τριμήκληνης | Α | Γ | Τριμήκληνη | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 241 | N241 | Νηπ. Πάφος Α΄ | Α | Ε | Δήμος Πάφου | 90 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 242 | N242 | Νηπ. Πάφος Ε΄- Αγίου Δημητρίου | Α | Ε | Δήμος Πάφου | 41 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 243 | N243 | Νηπ. Πάφος Γ΄ - Αποστόλου Παύλου | Α | Ε | Δήμος Πάφου | 96 | 4 | | | | | | | Ναι | 04/10/29 | Ναι | Οχι |
| 244 | N244 | Νηπ. Πάφος Δ΄ - Κάτω Περβολιών | Α | Ε | Δήμος Πάφου | 70 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 245 | N245 | Νηπ. Πάφος Η΄ - Αναβαργός | Α | Ε | Δήμος Πάφου | 73 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 246 | N246 | Νηπ. Πάφος Θ΄ - Πετρίδειο | Α | Ε | Δήμος Πάφου | 122 | 5 | | | | | | | Οχι | | Ναι | Οχι |
| 247 | N247 | Νηπ. Πάφος Ι΄ | Α | Ε | Δήμος Πάφου | 75 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 248 | N248 | Νηπ. Πάφος ΙΑ' | Α | Ε | Δήμος Πάφου | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 249 | N249 | Νηπ. Πάφος ΙΒ΄- Πεύκιος Γεωργιάδης | Α | Ε | Δήμος Πάφου | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 250 | N250 | Νηπ. Πάφος ΙΓ' | Α | Ε | Δήμος Πάφου | 45 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 251 | N251 | Νηπ. Πάφος Στ΄ - Κάτω Πάφου | Α | Ε | Δήμος Πάφου | 47 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 252 | N252 | Νηπ. Γεροσκήπου Α΄ | Α | Ε | Δήμος Γεροσκήπου | 72 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 253 | N253 | Νηπ. Γεροσκήπου Β΄ | Α | Ε | Δήμος Γεροσκήπου | 92 | 4 | | | | | | | Οχι | | Ναι | Οχι |
| 254 | N254 | Νηπ. Αγία Μαρίνα Χρυσοχούς | Α | Ε | Αγία Μαρίνα Χρυσοχούς | 11 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 255 | N255 | Νηπ. Αργάκα | Α | Ε | Αργάκα | 25 | 1 | | | | | | | Ναι | 15/01/25 | Ναι | Οχι |
| 256 | N256 | Νηπ. Γιόλου | Α | Ε | Γιόλου | 24 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 257 | N257 | Νηπ. Δρούσεια | Α | Ε | Δρούσια | 13 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 258 | N258 | Νηπ. Έμπα | Α | Ε | Έμπα | 71 | 3 | | | | | | | Οχι | | Ναι | Οχι |

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| 259 | N259 | Νηπ. Ίνεια | Α | Ε | Ίνια | 7 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 260 | N260 | Νηπ. Κισσόνεργα | Α | Ε | Κισσόνεργα | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 261 | N261 | Νηπ. Κονιά | Α | Ε | Κονιά | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 262 | N262 | Νηπ. Κούκλια | Α | Ε | Κούκλια | 16 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 263 | N263 | Νηπ. Μανδριά | Α | Ε | Μανδριά | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 264 | N264 | Νηπ. Μεσόγη | Α | Ε | Μεσόγη | 49 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 265 | N265 | Νήπ. Παναγιά | Α | Ε | Παναγιά | 11 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 266 | N266 | Νηπ. Πέγεια | Α | Ε | Δήμος Πέγειας | 48 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 267 | N267 | Νηπ. Πολέμι | Α | Ε | Πολέμι | 23 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 268 | N268 | Νηπ. Πόλη Χρυσοχούς | Α | Ε | Δήμος Πόλης Χρυσοχούς | 67 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 269 | N269 | Νηπ. Στρουμπί | Α | Ε | Στρουμπί | 15 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 270 | N270 | Νηπ. Τάλα | Α | Ε | Τάλα | 24 | 1 | | | | | | | Ναι | 23/09/24 | Ναι | Οχι |
| 271 | N271 | Νηπ. Τίμη | Α | Ε | Τίμη | 34 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 272 | N272 | Νηπ. Τσάδα - Κοίλη - Ευαγόρας Παλληκαρίδης | Α | Ε | Τσάδα | 25 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 273 | N273 | Νηπ. Χλώρακα-Λέμπα Αγίου Στεφάνου | Α | Ε | Χλώρακα | 74 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 274 | N274 | Νηπ. Χλώρακας Αγίου Νικολάου | Α | Ε | Χλώρακα | 50 | 2 | | | | | | | Οχι | | Ναι | Οχι |
| 275 | N275 | Νηπ. Χολέτρια | Α | Ε | Χολέτρια | 9 | 1 | | | | | | | Οχι | | Ναι | Οχι |
| 276 | M1 | Γυμν. Αγλαντζιάς | Γ1 | Α | Δήμος Αγλατζιάς | 391 | 11 | 4 | 10 | 4 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 277 | M2 | Γυμν. Φανερωμένης | Γ1 | Α | Δήμος Λευκωσίας | 63 | 4 | 2 | 5 | 3 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 278 | M3 | Γυμν. Παλουριώτισσας | Γ1 | Α | Δήμος Λευκωσίας | 446 | 18 | 7 | 10 | 5 | 1 | | 0 | Οχι | | Ναι | Οχι |
| 279 | M4 | Γυμν. Ακρόπολης | Γ1 | Α | Δήμος Στροβόλου | 393 | 17 | 8 | 9 | 3 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 280 | M5 | Γυμν. Μακεδονίτισσας | Γ1 | Α | Δήμος Έγκωμης | 463 | 18 | 7 | 10 | 3 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 281 | M6 | Γυμν. Έγκωμης | Γ1 | Α | Δήμος Έγκωμης | 429 | 19 | 6 | 10 | 2 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 282 | M7 | Γυμν. Μακαρίου, Πλατύ | Γ1 | Α | Δήμος Αγλατζιάς | 400 | 14 | 7 | 10 | 4 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 283 | M8 | Γυμν. Αγ. Δομετίου | Γ1 | Α | Δήμος Αγίου Δομετίου | 156 | 9 | 4 | 8 | 3 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 284 | M9 | Γυμν. Ανθούπολης | Γ1 | Α | Δήμος Λακατάμειας | 260 | 12 | 6 | 10 | 6 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 285 | M10 | Γυμν. Αγ. Βασιλείου Στρ. | Γ1 | Α | Δήμος Στροβόλου | 306 | 15 | 6 | 10 | 5 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 286 | M11 | Γυμν. Αγ. Στυλιανού | Γ1 | Α | Δήμος Στροβόλου | 350 | 17 | 5 | 10 | 5 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 287 | M12 | Γυμν. Σταυρού Στρ. | Γ1 | Α | Δήμος Στροβόλου | 237 | 12 | 6 | 10 | 5 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 288 | M13 | Γ. Κωνσταντινουπόλεως | Γ1 | Α | Δήμος Στροβόλου | 221 | 11 | 6 | 9 | 5 | 1 | | 1 | Οχι | | Οχι | Οχι |
| 289 | M14 | Γ. Διανέλλου και | Γ1 | Α | Δήμος Στροβόλου | 253 | 11 | 6 | 10 | 5 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 290 | M15 | Γυμν. Λατσιών | Γ1 | Α | Δήμος Λατσιών | 416 | 16 | 6 | 10 | 6 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 291 | M16 | Γυμν. Αρχαγγέλου | Γ1 | Α | Δήμος Λακατάμειας | 450 | 19 | 5 | 11 | 6 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 292 | M17 | Γυμν.Αγ.Ιωάννου Χρυσ/μου | Γ1 | Α | Δήμος Λακατάμειας | 266 | 12 | 7 | 10 | 7 | 5 | | 1 | Οχι | | Ναι | Οχι |
| 293 | M18 | Γυμν. Γερίου | Γ1 | Α | Δήμος Γερίου | 222 | 10 | 6 | 8 | 3 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 294 | M19 | Γυμν.Πέρα Χωρίου Νήσου | Γ1 | Α | Πέρα Χωριό Νήσου | 498 | 15 | 7 | 11 | 5 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 295 | M20 | Γυμν. Αγ. Βαρβάρας | Γ1 | Α | Αγία Βαρβάρα | 413 | 15 | 8 | 10 | 5 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 296 | M21 | Β' Περιφ. Γυμν. Λ/σίας | Γ1 | Α | Μαλούντα | 419 | 16 | 5 | 10 | 3 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 297 | M22 | Γυμν. Σολέας | Γ1 | Α | Ευρύχου | 173 | 9 | 5 | 8 | 4 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 298 | M23 | Γυμν. Ακακίου | Γ1 | Α | Ακάκι | 222 | 12 | 7 | 9 | 6 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 299 | M24 | Π.Γυμν.Κοκκινοτριμιθιάς | Γ1 | Α | Κοκκινοτριμιθιά | 344 | 15 | 4 | 10 | 4 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 300 | M25 | Γυμν. ΝΑΡΕΚ | Γ1 | Α | Δήμος Στροβόλου | 28 | - | - | - | - | - | - | - | Οχι | | Ναι | Οχι |
| 301 | M26 | Λανίτειο Γυμν. | Γ1 | Γ | Δήμος Λεμεσού | 553 | 25 | 9 | 10 | 2 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 302 | M27 | Γυμν. Καλογεροπούλου | Γ1 | Γ | Δήμος Μέσα Γειτονιάς | 401 | 14 | 5 | 9 | 2 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 303 | M28 | Γυμν. Αγ. Ιωάννη | Γ1 | Γ | Δήμος Κάτω Πολεμιδιών | 271 | 13 | 6 | 11 | 7 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 304 | M29 | Γυμν. Νεάπολης | Γ1 | Γ | Δήμος Λεμεσού | 297 | 15 | 5 | 9 | 2 | 2 | | 0 | Οχι | | Ναι | Οχι |
| 305 | M30 | Γυμν. Καθολικής | Γ1 | Γ | Δήμος Λεμεσού | 329 | 12 | 5 | 10 | 4 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 306 | M31 | Γυμν. Πολεμιδιών | Γ1 | Γ | Δήμος Κάτω Πολεμιδιών | 391 | 15 | 7 | 11 | 7 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 307 | M32 | Τσίρειο Γυμν. | Γ1 | Γ | Δήμος Λεμεσού | 278 | 15 | 5 | 10 | 4 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 308 | M33 | Γυμν. Αγ. Αντωνίου | Γ1 | Γ | Δήμος Λεμεσού | 146 | 7 | 5 | 8 | 5 | 2 | | 0 | Οχι | | Ναι | Οχι |
| 309 | M34 | Θέκλειο Γυμν. | Γ1 | Γ | Δήμος Λεμεσού | 197 | 9 | 5 | 6 | 4 | 0 | | 0 | Οχι | | Ναι | Οχι |
| 310 | M35 | Γυμν. Λινόπετρας | Γ1 | Γ | Δήμος Αγίου Αθανασίου | 514 | 22 | 6 | 10 | 4 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 311 | M36 | Γυμν. Αγ. Αθανασίου | Γ1 | Γ | Δήμος Αγίου Αθανασίου | 423 | 18 | 5 | 10 | 3 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 312 | M37 | Γυμν. Αγ. Βαρβάρας | Γ1 | Γ | Δήμος Λεμεσού | 251 | 12 | 7 | 10 | 5 | 5 | | 0 | Οχι | | Ναι | Οχι |
| 313 | M38 | Γυμνάσιο Αγίας Φυλάξεως | Γ1 | Γ | Δήμος Λεμεσού | 356 | 16 | 7 | 10 | 4 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 314 | M39 | Γυμνάσιο Αγίου Νεοφύτου | Γ1 | Γ | Δήμος Κάτω Πολεμιδιών | 292 | 12 | 5 | 10 | 8 | 4 | | 1 | Οχι | | Ναι | Οχι |
| 315 | M40 | Γυμν. Επισκοπής | Γ1 | Γ | Επισκοπή Λ/σού | 311 | 14 | 4 | 10 | 6 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 316 | M41 | Γυμνάσιο Ζακακίου | Γ1 | Γ | Δήμος Λεμεσού | 291 | 13 | 5 | 10 | 6 | 2 | | 1 | Οχι | | Ναι | Οχι |

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| 317 | M42 | Γυμν. Τραχωνίου | Γ1 | Γ | Τραχώνι | 329 | 13 | 4 | 9 | 7 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 318 | M43 | Γυμν. ΄Υψωνα | Γ1 | Γ | Δήμος Ύψωνα | 471 | 13 | 4 | 10 | 5 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 319 | M44 | Γυμν. Λύκειο Ομόδους ** | Γ1 | Γ | Όμοδος | 60 | 8 | 4 | 6 | 5 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 320 | M45 | Γυμν. Λύκειο Αγρού ** | Γ1 | Γ | Αγρός | 85 | 14 | 5 | 9 | 9 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 321 | M46 | Γυμν. Δροσιάς | Γ1 | Β | Δήμος Λάρνακας | 427 | 14 | 6 | 9 | 5 | 2 | | 0 | Οχι | | Ναι | Οχι |
| 322 | M47 | Ευρυβιάδειο Γυμν. | Γ1 | Β | Δήμος Λάρνακας | 179 | 12 | 6 | 10 | 4 | 0 | | 1 | Ναι | - | Οχι | Οχι |
| 323 | M48 | Γυμν. Φανερωμένης | Γ1 | Β | Δήμος Λάρνακας | 175 | 9 | 5 | 6 | 6 | 0 | | 0 | Οχι | | Ναι | Οχι |
| 324 | M49 | Γυμν. Λειβαδιών | Γ1 | Β | Δήμος Λειβαδιών | 488 | 12 | 5 | 10 | 6 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 325 | M50 | Γυμν.Πετράκη Κυπριανού | Γ1 | Β | Δήμος Λάρνακας | 436 | 18 | 12 | 10 | 11 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 326 | M51 | Γυμν. Βεργίνας | Γ1 | Β | Δήμος Λάρνακας | 551 | 19 | 8 | 11 | 5 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 327 | M52 | Γυμν. Αραδίππου | Γ1 | Β | Δήμος Αραδίππου | 557 | 9 | 8 | 13 | 11 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 328 | M53 | Γυμν. Κιτίου | Γ1 | Β | Κίτι | 480 | 13 | 5 | 11 | 9 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 329 | M54 | Γυμν. Αθηαίνου | Γ1 | Β | Δήμος Αθηένου | 210 | 8 | 5 | 7 | 6 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 330 | M55 | Γυμν. Ξυλοτύμπου | Γ1 | Β | Ξυλοτύμβου | 350 | 14 | 4 | 9 | 5 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 331 | M56 | Γυμν. Ξυλοφάγου | Γ1 | Β | Ξυλοφάγου | 333 | 15 | 6 | 10 | 5 | 3 | | 1 | Οχι | | Ναι | Οχι |
| 332 | M57 | Γυμν. Λύκειο Λευκάρων ** | Γ1 | Β | Δήμος Πάνω Λευκάρων | 160 | 15 | 6 | 8 | 6 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 333 | M58 | Γυμν. Παραλιμνίου | Γ1 | Δ | Δήμος Παραλιμνίου | 649 | 21 | 6 | 13 | 5 | 3 | | 1 | Ναι | 10/06/30 | Ναι | Οχι |
| 334 | M59 | Γυμν. Κοκκινοχωριών | Γ1 | Δ | Φρέναρος (Κοκκινοχώρια) | 383 | 16 | 6 | 10 | 6 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 335 | M60 | Γυμνάσιο Δερύνειας | Γ1 | Δ | Δερύνεια | 362 | 15 | 5 | 10 | 6 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 336 | M61 | Γυμν. Λύκειο Ριζοκαρπάσου** | Γ1 | Δ | Ριζοκάρπασο | 7 | - | - | - | - | - | | - | Οχι | | Ναι | Οχι |
| 337 | M62 | Γυμν. Αγ. Θεοδώρου | Γ1 | Ε | Δήμος Πάφου | 522 | 18 | 6 | 10 | 4 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 338 | M63 | Νικολαΐδειο Γυμν. | Γ1 | Ε | Δήμος Πάφου | 314 | 13 | 3 | 7 | 3 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 339 | M64 | Γυμν. Απ. Παύλου | Γ1 | Ε | Δήμος Πάφου | 614 | 22 | 8 | 9 | 5 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 340 | M65 | Γυμν. Γεροσκήπου | Γ1 | Ε | Δήμος Γεροσκήπου | 409 | 12 | 6 | 10 | 4 | 4 | | 1 | Οχι | | Οχι | Οχι |
| 341 | M66 | Γυμν. Εμπας | Γ1 | Ε | Έμπα | 432 | 18 | 6 | 10 | 2 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 342 | M67 | Γυμν.Παναγίας Θεοσκ/στης | Γ1 | Ε | Δήμος Πάφου | 391 | 16 | 6 | 9 | 4 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 343 | M68 | Γυμν. Πόλης Χρυσοχούς | Γ1 | Ε | Δήμος Πόλης Χρυσοχούς | 298 | 12 | 4 | 8 | 2 | 1 | | 0 | Οχι | | Ναι | Οχι |
| 344 | M69 | Γυμν. Λύκειο Πολεμίου ** | Γ1 | Ε | Πολέμι | 416 | 10 | 5 | 7 | 5 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 345 | M70 | Γυμν. Λύκειο Κ. Πύργου ** | Γ1 | Ε | Κάτω Πύργος Λ/σίας | 24 | 6 | 3 | 4 | 5 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 346 | M71 | Παγκύπριο Γυμνάσιο | Γ2 | Α | Δήμος Λευκωσίας | 352 | 26 | 7 | 10 | 8 | 2 | | 0 | Οχι | | Οχι | Οχι |
| 347 | M72 | Λύκειο Παλουριώτισσας | Γ2 | Α | Δήμος Λευκωσίας | 332 | 18 | 9 | 10 | 9 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 348 | M73 | Λύκειο Ακρόπολης | Γ2 | Α | Δήμος Στροβόλου | 348 | 24 | 9 | 11 | 9 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 349 | M74 | Ενιαίο Λύκειο Κύκκου Α' | Γ2 | Α | Δήμος Έγκωμης | 410 | 22 | 9 | 11 | 7 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 350 | M75 | Ενιαίο Λύκειο Κύκκου Β' | Γ2 | Α | Δήμος Έγκωμης | 536 | 26 | 12 | 13 | 9 | 2 | | 2 | Οχι | | Ναι | Οχι |
| 351 | M76 | Λ.Αρχαγγέλου Απ. Μάρκου | Γ2 | Α | Δήμος Στροβόλου | 542 | 14 | 10 | 14 | 11 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 352 | M77 | Λύκειο Μακαρίου Γ' | Γ2 | Α | Δήμος Στροβόλου | 565 | 21 | 10 | 11 | 10 | 2 | | 1 | Ναι | - | Ναι | Οχι |
| 353 | M78 | Λύκειο Εθν. Κυπριανού | Γ2 | Α | Δήμος Στροβόλου | 478 | 15 | 8 | 11 | 17 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 354 | M79 | Λύκειο Απ. Βαρνάβα | Γ2 | Α | Δήμος Στροβόλου | 467 | 26 | 10 | 10 | 5 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 355 | M80 | Λύκειο Παλιομετόχου | Γ2 | Α | Παλιομέτοχο | 463 | 25 | 8 | 11 | 9 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 356 | M81 | Λύκειο Αγ.Γεωργίου Λακατ. | Γ2 | Α | Δήμος Λακατάμειας | 576 | 25 | 8 | 10 | 8 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 357 | M82 | Λύκειο Λατσιών | Γ2 | Α | Δήμος Λατσιών | 492 | 21 | 12 | 10 | 10 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 358 | M83 | Λύκειο Σολέας | Γ2 | Α | Ευρύχου | 119 | 5 | 7 | 7 | 9 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 359 | M84 | Λύκειο Ιδαλίου | Γ2 | Α | Δήμος Ιδαλίου | 606 | 24 | 11 | 11 | 9 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 360 | M85 | Λύκειο Παραλιμνίου | Γ2 | Δ | Δήμος Παραλιμνίου | 533 | 16 | 12 | 12 | 9 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 361 | M86 | Λύκειο Φρενάρους | Γ2 | Δ | Φρέναρος (Κοκκινοχώρια) | 365 | 17 | 7 | 9 | 9 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 362 | M87 | Παγκύπριο Λύκειο Λ/κας | Γ2 | Β | Δήμος Λάρνακας | 431 | 22 | 10 | 10 | 8 | 1 | | 0 | Οχι | | Ναι | Οχι |
| 363 | M88 | Λύκειο Αγ. Γεωργίου | Γ2 | Β | Δήμος Λάρνακας | 404 | 21 | 13 | 13 | 11 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 364 | M89 | Λύκειο Αρχ. Μακαρίου Γ' | Γ2 | Β | Δήμος Λάρνακας | 445 | 18 | 8 | 11 | 10 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 365 | M90 | Λύκειο Βεργίνας | Γ2 | Β | Δήμος Λάρνακας | 470 | 24 | 8 | 11 | 7 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 366 | M91 | Λύκειο Λιβαδιών | Γ2 | Β | Δήμος Λειβαδιών | 572 | 18 | 9 | 12 | 9 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 367 | M92 | Λύκειο Αραδίππου | Γ2 | Β | Δήμος Αραδίππου | 496 | 18 | 7 | 11 | 9 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 368 | M93 | Λανίτειο Λύκειο | Γ2 | Γ | Δήμος Λεμεσού | 796 | 31 | 9 | 14 | 8 | 4 | | 0 | Οχι | | Ναι | Οχι |
| 369 | M94 | Λύκ.Απ.Πέτρου & Παύλου | Γ2 | Γ | Δήμος Λεμεσού | 471 | 11 | 7 | 9 | 11 | 1 | | 0 | Οχι | | Ναι | Οχι |
| 370 | M95 | Λύκειο Αγ. Ιωάννη | Γ2 | Γ | Δήμος Λεμεσού | 337 | 22 | 9 | 11 | 12 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 371 | M96 | Λύκειο Αγ. Νικολάου | Γ2 | Γ | Δήμος Λεμεσού | 393 | 11 | 7 | 11 | 9 | 1 | | 1 | Οχι | | Ναι | Οχι |

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| 372 | M97 | Λύκειο Πολεμιδίων | Γ2 | Γ | Δήμος Κάτω Πολεμιδιών | 318 | 22 | 8 | 11 | 10 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 373 | M98 | Λύκειο Αγ. Αντωνίου | Γ2 | Γ | Δήμος Λεμεσού | 205 | 17 | 6 | 10 | 6 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 374 | M99 | Λύκειο Αγ. Σπυρίδωνα | Γ2 | Γ | Δήμος Κάτω Πολεμιδιών | 428 | 20 | 9 | 10 | 18 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 375 | M100 | Λύκειο Λινόπετρας | Γ2 | Γ | Δήμος Αγίου Αθανασίου | 683 | 16 | 9 | 11 | 13 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 376 | M101 | Λύκειο Αγίας Φυλάξεως | Γ2 | Γ | Δήμος Λεμεσού | 437 | 22 | 9 | 9 | 8 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 377 | M102 | Λύκειο Κολοσσίου | Γ2 | Γ | Κολόσσι | 620 | 12 | 9 | 12 | 15 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 378 | M103 | Εμπορ. Σχολή Λεμύθου** | Γ2 | Γ | Λεμίθου | 61 | 6 | 4 | 5 | 5 | 0 | | 0 | Οχι | | Ναι | Οχι |
| 379 | M104 | Λύκειο Α' Εθν. Μακαρίου | Γ2 | Ε | Δήμος Πάφου | 677 | 18 | 7 | 10 | 11 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 380 | M105 | Λύκειο Κύκκου Πάφου | Γ2 | Ε | Δήμος Πάφου | 210 | 6 | 3 | 7 | 5 | 0 | | 1 | Οχι | | Ναι | Οχι |
| 381 | M106 | Λύκειο Αγ. Νεοφύτου | Γ2 | Ε | Δήμος Πάφου | 369 | 13 | 7 | 10 | 10 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 382 | M107 | Λύκειο και Τεχν.Σχ.Πόλης | Γ2 | Ε | Δήμος Πόλης | 216 | 19 | 7 | 6 | 6 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 383 | M108 | Λύκειο Έμπας | Γ2 | Ε | Έμπα | 355 | 12 | 11 | 11 | 9 | 1 | | 1 | Οχι | | Ναι | Οχι |
| 384 | M109 | Λύκειο Γεροσκήπου | Γ2 | Ε | Δήμος Γεροσκήπου | 303 | 16 | 6 | 10 | 12 | 2 | | 1 | Οχι | | Ναι | Οχι |
| 385 | Δ1 | Αγία Νάπα - Αντώνη Τσόκκου | Β | Δ | Αγία Νάπα | 328 | 16 | | 5 | | 4 | | 1 | Οχι | | Ναι | Οχι |
| 386 | Δ2 | Άγιος Γεώργιος - Βρυσούλες - Αχερίτου | Β | Δ | Βρυσούλες | 98 | 6 | | 2 | | 4 | | 1 | Ναι | - | Ναι | Οχι |
| 387 | Δ3 | Αυγόρου Α΄ | Β | Δ | Αυγόρου | 191 | 12 | | 5 | | 2 | | 1 | Μέρος | 08/12/26 | Ναι | Οχι |
| 388 | Δ4 | Αυγόρου Β΄ | Β | Δ | Αυγόρου | 158 | 12 | | 6 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 389 | Δ5 | Δάσος Άχνας - «Φώτης Πίττας» | Β | Δ | Δάσος Άχνας | 155 | 11 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 390 | Δ6 | Δερύνεια Α΄ | Β | Δ | Δερύνεια | 99 | 6 | | 4 | | 3 | | 0 | Οχι | | Ναι | Οχι |
| 391 | Δ7 | Δερύνεια Β΄ | Β | Δ | Δερύνεια | 104 | 8 | | 5 | | 2 | | 0 | Οχι | | Ναι | Οχι |
| 392 | Δ8 | Δερύνεια Γ΄ | Β | Δ | Δερύνεια | 154 | 11 | | 5 | | 2 | | 0 | Οχι | | Ναι | Οχι |
| 393 | Δ9 | Λιοπέτρι Α΄ | Β | Δ | Λιοπέτρι | 166 | 10 | | 6 | | 4 | | 1 | Οχι | | Ναι | Οχι |
| 394 | Δ10 | Λιοπέτρι Β΄ | Β | Δ | Λιοπέτρι | 176 | 11 | | 4 | | 3 | | 1 | Οχι | | Οχι | Οχι |
| 395 | Δ11 | Παραλίμνι Α΄ | Β | Δ | Παραλίμνι | 315 | 12 | | 5 | | 3 | | 1 | Μέρος | 11/12/26 | Ναι | Οχι |
| 396 | Δ12 | Παραλίμνι Β΄ | Β | Δ | Παραλίμνι | 288 | 13 | | 5 | | 3 | | 1 | Οχι | | Ναι | Ναι |
| 397 | Δ13 | Παραλίμνι Γ΄ | Β | Δ | Παραλίμνι | 227 | 12 | | 4 | | 4 | | 1 | Οχι | | Ναι | Οχι |
| 398 | Δ14 | Παραλίμνι Δ΄ (ΔΡΑ.Σ.Ε.) | Β | Δ | Παραλίμνι | 270 | 15 | | 5 | | 3 | | 1 | Οχι | | Οχι | Οχι |
| 399 | Δ15 | Σωτήρα Α΄ | Β | Δ | Σωτήρα | 159 | 10 | | 5 | | 4 | | 0 | Οχι | | Ναι | Οχι |
| 400 | Δ16 | Σωτήρα Β΄ | Β | Δ | Σωτήρα | 147 | 7 | | 3 | | 4 | | 0 | Οχι | | Ναι | Οχι |
| 401 | Δ17 | Σωτήρα Γ΄ (Ενιαίο Ολοήμερο) | Β | Δ | Σωτήρα | 99 | 9 | | 7 | | 3 | | 1 | Οχι | | Ναι | Ναι |
| 402 | Δ18 | Φρέναρος | Β | Δ | Φρέναρος | 285 | 11 | | 6 | | 2 | | 0 | Οχι | | Ναι | Οχι |
| 403 | Δ19 | Άγιοι Ανάργυροι - «Μιχάλης Κακογιάννης» | Β | Β | Λάρνακα | 196 | 11 | | 6 | | 3 | | | Οχι | | Ναι | Οχι |
| 404 | Δ20 | Άγιος Γεώργιος | Β | Β | Λάρνακα | 100 | 7 | | 5 | | 3 | | 1 | Οχι | | Ναι | Ναι |
| 405 | Δ21 | Άγιος Ιωάννης | Β | Β | Λάρνακα | 149 | 8 | | 5 | | 4 | | 1 | Οχι | | Ναι | Οχι |
| 406 | Δ22 | Άγιος Λάζαρος Α΄ - Χριστόφορου Χριστοφίδη | Β | Β | Λάρνακα | 121 | | | 2 | | 2 | | | Ναι | 07/04/26 | Ναι | Οχι |
| 407 | Δ23 | Άγιος Λάζαρος Β΄ (ΔΡΑ.Σ.Ε.) | Β | Β | Λάρνακα | 130 | 7 | | 5 | | | | | Οχι | | Οχι | Οχι |
| 408 | Δ24 | Δροσιά (ΚΑ) | Β | Β | Λάρνακα | 295 | 9 | | 0 | | 3 | | | Ναι | 12/04/28 | Οχι | Οχι |
| 409 | Δ25 | Δροσιά (ΚΒ) - «Μιχαλάκης Παρίδης» | Β | Β | Λάρνακα | 304 | 12 | | 7 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 410 | Δ26 | Εθνάρχης Μακάριος Γ΄ (ΚΑ) (ΔΡΑ.Σ.Ε.) | Β | Β | Λάρνακα | 104 | 6 | | 3 | | 1 | | | Οχι | | Ναι | Οχι |
| 411 | Δ27 | Εθνάρχης Μακάριος Γ΄ (ΚΒ) (ΔΡΑ.Σ.Ε.) | Β | Β | Λάρνακα | 95 | 6 | | 6 | | 3 | | | Οχι | | Ναι | Οχι |
| 412 | Δ28 | Ζήνων | Β | Β | Λάρνακα | 241 | 12 | | 5 | | 1 | | | Οχι | | Οχι | Οχι |
| 413 | Δ29 | Καθαρή - Δημήτρη Λιπέρτη | Β | Β | Λάρνακα | 304 | 12 | | 6 | | 2 | | 1 | Οχι | | Ναι | Ναι |
| 414 | Δ30 | Καλογεράς (ΚΑ) (ΔΡΑ.Σ.Ε.) | Β | Β | Λάρνακα | 73 | 6 | | 1 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 415 | Δ31 | Καλογεράς (ΚΒ) (ΔΡΑ.Σ.Ε.) | Β | Β | Λάρνακα | 68 | 7 | | 1 | | 20 | | 1 | Οχι | | Ναι | Οχι |
| 416 | Δ32 | Καμάρες | Β | Β | Λάρνακα | 362 | 15 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 417 | Δ33 | Πρόδρομος (ΚΑ) (ΔΡΑ.Σ.Ε.) | Β | Β | Λάρνακα | 105 | 6 | | 2 | | 2 | | | Οχι | | Ναι | Οχι |
| 418 | Δ34 | Πρόδρομος (ΚΒ) (ΔΡΑ.Σ.Ε.) | Β | Β | Λάρνακα | 125 | 6 | | 5 | | 0 | | | Οχι | | Ναι | Οχι |
| 419 | Δ35 | Σωτήρος - Τούλας Χαραλάμπους (ΔΡΑ.Σ.Ε.) | Β | Β | Λάρνακα | 212 | 12 | | 3 | | 2 | | | Οχι | | Ναι | Οχι |
| 420 | Δ36 | Αγγλισίδες | Β | Β | Αγγλισίδες | 93 | 6 | | 2 | | 1 | | | Οχι | | Ναι | Οχι |
| 421 | Δ37 | Αγία Άννα | Β | Β | Αγία Άννα | 30 | | | | | 1 | | | Οχι | | Ναι | Οχι |
| 422 | Δ38 | Άγιος Θεόδωρος | Β | Β | Άγιος Θεόδωρος | 47 | 3 | | 2 | | | | | Οχι | | Οχι | Οχι |
| 423 | Δ39 | Αθηένου (ΚΑ) | Β | Β | Αθηένου | 189 | 9 | | 5 | | 0 | | | Ναι | 18/04/26 | Ναι | Ναι |
| 424 | Δ40 | Αθηένου (ΚΒ) | Β | Β | Αθηένου | 178 | 8 | | 5 | | 2 | | | Ναι | 18/04/26 | Ναι | Ναι |
| 425 | Δ41 | Αλεθρικό | Β | Β | Αλεθρικό | 141 | 8 | | 3 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 426 | Δ42 | Αναφωτίδα | Β | Β | Αναφωτίδα | 49 | 5 | | 4 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 427 | Δ43 | Αραδίππου Α΄ | Β | Β | Αραδίππου | 282 | 12 | | 3 | | 1 | | | Οχι | | Ναι | Οχι |
| 428 | Δ44 | Αραδίππου Β΄ | Β | Β | Αραδίππου | 245 | 12 | | 4 | | | | 1 | Οχι | | Ναι | Οχι |
| 429 | Δ45 | Αραδίππου Γ΄ | Β | Β | Αραδίππου | 289 | 15 | | 4 | | 1 | | | Οχι | | Ναι | Οχι |

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| 430 | Δ46 | Αραδίππου Δ΄ - Αγίου Φανουρίου | Β | Β | Αραδίππου | 430 | 16 | | 5 | | 4 | | | Οχι | | Ναι | Οχι |
| 431 | Δ47 | Αραδίππου Ε΄ - Αγίων Αυξεντίου και Ευσταθίου | Β | Β | Αραδίππου | 314 | 15 | | 5 | | 2 | | 1 | Οχι | | Ναι | Ναι |
| 432 | Δ48 | Βορόκληνη (ΔΡΑ.Σ.Ε.) | Β | Β | Βορόκληνη | 437 | 18 | | 4 | | 2 | | | Μέρος | 08/12/26 | Ναι | Ναι |
| 433 | Δ49 | Δρομολαξιά Α΄ | Β | Β | Δρομολαξιά | 122 | 6 | | 3 | | 2 | | | Οχι | | Ναι | Οχι |
| 434 | Δ50 | Δρομολαξιά Β΄ | Β | Β | Δρομολαξιά | 115 | 6 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 435 | Δ51 | Μενεού | Β | Β | Μενεού | 203 | 11 | | 5 | | 1 | | 1 | Οχι | | Οχι | Οχι |
| 436 | Δ52 | Ζύγι | Β | Β | Ζύγι | 54 | 4 | | 2 | | 2 | | | Οχι | | Οχι | Οχι |
| 437 | Δ53 | Καλαβασός | Β | Β | Καλαβασός | 33 | 3 | | 2 | | 1 | | | Οχι | | Οχι | Οχι |
| 438 | Δ54 | Καλό Χωριό | Β | Β | Καλό Χωριό Λάρνακας | 127 | 7 | | 5 | | 1 | | | Μέρος | 05/11/28 | Ναι | Οχι |
| 439 | Δ55 | Κελλιά | Β | Β | Κελλιά | 26 | 2 | | 1 | | 2 | | | Οχι | | Ναι | Οχι |
| 440 | Δ56 | Κίτι | Β | Β | Κίτι | 360 | 15 | | 5 | | 0 | | 1 | Οχι | | Ναι | Οχι |
| 441 | Δ57 | Κόρνος | Β | Β | Κόρνος | 126 | 7 | | 2 | | 3 | | | Οχι | | Ναι | Οχι |
| 442 | Δ58 | Κοφίνου - «Μιχαλοπούλειο» (ΔΡΑ.Σ.Ε.) | Β | Β | Κοφίνου | 96 | 5 | | 3 | | 2 | | 1 | Οχι | | Οχι | Ναι |
| 443 | Δ59 | Λεύκαρα Πάνω | Β | Β | Πάνω Λεύκαρα | 53 | 7 | | 3 | | 3 | | | Οχι | | Ναι | Οχι |
| 444 | Δ60 | Λιβάδια (ΚΑ) (ΔΡΑ.Σ.Ε.) | Β | Β | Λιβάδια | 274 | 12 | | 1 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 445 | Δ61 | Λιβάδια (ΚΒ) (ΔΡΑ.Σ.Ε.) | Β | Β | Λιβάδια | 266 | 11 | | 3 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 446 | Δ62 | Μαζωτός (Περιφερειακό) | Β | Β | Μαζωτός | 49 | 4 | | 3 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 447 | Δ63 | Μαρώνι - Ψεματισμένος | Β | Β | Μαρώνι | 56 | 3 | | 0 | | 0 | | | Οχι | | Ναι | Οχι |
| 448 | Δ64 | Μοσφιλωτή | Β | Β | Μοσφιλωτή | 91 | 6 | | 4 | | 0 | | | Οχι | | Ναι | Οχι |
| 449 | Δ65 | Ξυλοτύμβου Α΄ | Β | Β | Ξυλοτύμβου | 130 | 8 | | 4 | | 1 | | | Μέρος | 11/12/26 | Ναι | Οχι |
| 450 | Δ66 | Ξυλοτύμβου Β΄ | Β | Β | Ξυλοτύμβου | 114 | 7 | | 3 | | 1 | | | Οχι | | Ναι | Οχι |
| 451 | Δ67 | Ξυλοφάγου Α΄ | Β | Β | Ξυλοφάγου | 253 | 13 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 452 | Δ68 | Ξυλοφάγου Β΄ | Β | Β | Ξυλοφάγου | 202 | 11 | | 4 | | 2 | | | Μέρος | 02/11/25 | Ναι | Οχι |
| 453 | Δ69 | Ορμίδεια Α΄ | Β | Β | Ορμίδεια | 134 | 8 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 454 | Δ70 | Ορμίδεια Β΄ | Β | Β | Ορμίδεια | 115 | 7 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 455 | Δ71 | Περιβόλια | Β | Β | Περιβόλια | 141 | 1 | | 4 | | 2 | | | Οχι | | Οχι | Οχι |
| 456 | Δ72 | Πύλα | Β | Β | Πύλα | 137 | 7 | | 2 | | 0 | | | Οχι | | Ναι | Οχι |
| 457 | Δ73 | Πυργά | Β | Β | Πυργά | 74 | 6 | | 7 | | 1 | | | Οχι | | Ναι | Ναι |
| 458 | Δ74 | Τερσεφάνου | Β | Β | Τερσεφάνου | 94 | 6 | | 2 | | 3 | | | Οχι | | Οχι | Οχι |
| 459 | Δ75 | Τόχνη | Β | Β | Τόχνη | 22 | 2 | | 0 | | 1 | | | Οχι | | Οχι | Οχι |
| 460 | Δ76 | Τρούλλοι | Β | Β | Τρούλλοι | 86 | 8 | | 5 | | 0 | | | Οχι | | Ναι | Οχι |
| 461 | Δ77 | Χοιροκοιτία (ΕΟΣ) | Β | Β | Χοιροκοιτία | 77 | 6 | | 3 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 462 | Δ78 | Ψευδάς | Β | Β | Ψευδάς | 93 | 6 | | 2 | | 2 | | | Οχι | | Ναι | Οχι |
| 463 | Δ79 | Λεμεσός Α΄ (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 106 | 9 | | 8 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 464 | Δ80 | Λεμεσός Β΄ (ΚΑ) (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 112 | 7 | | 4 | | 2 | | | Οχι | | Ναι | Ναι |
| 465 | Δ81 | Λεμεσός Β΄ (ΚΒ) (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 153 | 8 | | 6 | | 3 | | 1 | Οχι | | Ναι | Ναι |
| 466 | Δ82 | Λεμεσός Γ΄ | Β | Γ | Λεμεσός | 209 | 12 | | 5 | | 2 | | | Οχι | | Οχι | Οχι |
| 467 | Δ83 | Λεμεσός Δ΄ (ΚΑ) (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 99 | 8 | | 2 | | 2 | | | Οχι | | Ναι | Οχι |
| 468 | Δ84 | Λεμεσός Δ΄ (ΚΒ) (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 168 | 9 | | 6 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 469 | Δ85 | Λεμεσός Ε΄ (ΚΑ) - Αγίου Ιωάννη (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 81 | 6 | | 2 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 470 | Δ86 | Λεμεσός Ε΄ (ΚΒ) - Αγίου Ιωάννη (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 121 | 7 | | 6 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 471 | Δ87 | Λεμεσός Στ΄ (ΚΑ) - Αγίου Νικολάου (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 113 | 7 | | 2 | | 1 | | | Οχι | | Οχι | Οχι |
| 472 | Δ88 | Λεμεσός Στ΄ (ΚΒ) - Αγίου Νικολάου (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 153 | 6 | | 4 | | 3 | | | Οχι | | Οχι | Οχι |
| 473 | Δ89 | Λεμεσός Ζ΄ (ΚΑ) - Αποστόλου Ανδρέα (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 116 | 7 | | 3 | | 3 | | | Οχι | | Ναι | Ναι |
| 474 | Δ90 | Λεμεσός Ζ΄ (ΚΒ) - Αποστόλου Ανδρέα (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 148 | 6 | | 6 | | 2 | | 1 | Οχι | | Ναι | Ναι |
| 475 | Δ91 | Λεμεσός Η΄ (ΚΑ) - Ομόνοιας (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 86 | 6 | | 0 | | 2 | | | Οχι | | Ναι | Οχι |
| 476 | Δ92 | Λεμεσός Η΄ (ΚΒ) - Ομόνοιας (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 140 | 6 | | 6 | | 0 | | 1 | Οχι | | Ναι | Οχι |
| 477 | Δ93 | Λεμεσός Θ΄ (ΚΑ) - Καψάλου | Β | Γ | Λεμεσός | 96 | 6 | | 0 | | 2 | | | Οχι | | Ναι | Οχι |
| 478 | Δ94 | Λεμεσός Θ΄ (ΚΒ) - Καψάλου | Β | Γ | Λεμεσός | 143 | 6 | | 6 | | 0 | | | Οχι | | Ναι | Οχι |
| 479 | Δ95 | Λεμεσός ΙΑ΄ (ΚΑ) - Τσίρειο | Β | Γ | Λεμεσός | 176 | 9 | | 2 | | 1 | | | Οχι | | Ναι | Ναι |
| 480 | Δ96 | Λεμεσός ΙΑ΄ (ΚΒ) - Τσίρειο | Β | Γ | Λεμεσός | 233 | 8 | | 6 | | 0 | | 1 | Οχι | | Ναι | Ναι |
| 481 | Δ97 | Λεμεσός ΙΒ΄ (ΚΑ) - Λανίτειο | Β | Γ | Λεμεσός | 102 | 6 | | 0 | | 1 | | | Οχι | | Οχι | Οχι |

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| 482 | Δ98 | Λεμεσός ΙΒ΄ (ΚΒ) - Λανίτειο | Β | Γ | Λεμεσός | 166 | 8 | | 5 | | 0 | | | Οχι | | Οχι | Οχι |
| 483 | Δ99 | Λεμεσός ΙΓ΄ (ΚΑ) - Αγίου Σπυρίδωνα Α΄ (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 101 | 7 | | 2 | | 1 | | | Οχι | | Οχι | Οχι |
| 484 | Δ100 | Λεμεσός ΙΓ΄ (ΚΒ) - Αγίου Σπυρίδωνα Α΄ (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 125 | 7 | | 6 | | 1 | | 1 | Οχι | | Οχι | Οχι |
| 485 | Δ101 | Λεμεσός ΙΣτ΄ - Ζακακίου - Πολύκαρπου Βλάχου | Β | Γ | Λεμεσός | 277 | 14 | | 6 | | 0 | | | Οχι | | Ναι | Οχι |
| 486 | Δ102 | Λεμεσός ΙΗ΄ - Αγίου Αντωνίου (ΔΡΑ.Σ.Ε.) | Β | Γ | Λεμεσός | 66 | 8 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 487 | Δ103 | Λεμεσός ΙΘ΄ - Αγίας Φυλάξεως | Β | Γ | Λεμεσός | 261 | 12 | | 5 | | 0 | | 1 | Οχι | | Ναι | Οχι |
| 488 | Δ104 | Λεμεσός Κ΄ - Αγίου Παντελεήμονα | Β | Γ | Λεμεσός | 328 | 16 | | 5 | | 1 | | | Οχι | | Οχι | Ναι |
| 489 | Δ105 | Λεμεσός ΚΒ΄ - Αγίου Γεωργίου | Β | Γ | Λεμεσός | 200 | 12 | | 5 | | 3 | | 1 | Οχι | | Οχι | Οχι |
| 490 | Δ106 | Λεμεσός ΚΓ΄ - Αγίου Σπυρίδωνα Β΄ | Β | Γ | Λεμεσός | 229 | 12 | | 7 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 491 | Δ107 | Λεμεσός ΚΕ΄ - Εκάλης | Β | Γ | Λεμεσός | 318 | 17 | | 5 | | 5 | | 1 | Οχι | | Ναι | Οχι |
| 492 | Δ108 | Λεμεσός ΚΣτ΄ - Παναγίας Τριχερούσας | Β | Γ | Λεμεσός | 344 | 16 | | 6 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 493 | Δ109 | Λεμεσός Ι΄ (ΚΑ) - Χαλκούτσας - Βασίλη Μιχαηλίδη | Β | Γ | Μέσα Γειτονιά | 181 | 9 | | 0 | | 1 | | | Ναι | 02/06/21 | Ναι | Οχι |
| 494 | Δ110 | Λεμεσός Ι΄ (ΚΒ) - Χαλκούτσας - Βασίλη Μιχαηλίδη | Β | Γ | Μέσα Γειτονιά | 145 | 8 | | 5 | | 0 | | 1 | Ναι | 02/06/21 | Ναι | Οχι |
| 495 | Δ111 | Λεμεσός ΙΔ΄ - Μέσα Γειτονιάς | Β | Γ | Λεμεσός | 104 | 8 | | 5 | | 1 | | | Οχι | | Οχι | Οχι |
| 496 | Δ112 | Λεμεσός ΚΑ΄ - Κοντοβάθεια | Β | Γ | Λεμεσός | 348 | 17 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 497 | Δ113 | Λεμεσός ΚΖ΄ - Τιμίου Προδρόμου | Β | Γ | Μέσα Γειτονιά | 311 | 14 | | 7 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 498 | Δ114 | Μέσα Γειτονιά ΚΘ΄ - Γ.Ν. Καλογερόπουλου | Β | Γ | Μέσα Γειτονιά | 134 | 12 | | 5 | | 1 | | | Ναι | 19/10/25 | Ναι | Οχι |
| 499 | Δ115 | «Άγιοι Ανάργυροι» Μονή - Μοναγρούλλι (Περιφερειακό) | Β | Γ | Μοναγρούλλι | 83 | 5 | | 2 | | 2 | | | Οχι | | Ναι | Οχι |
| 500 | Δ116 | Άγιος Αθανάσιος Α΄ | Β | Γ | Άγιος Αθανάσιος | 194 | 12 | | 5 | | 1 | | | Οχι | | Ναι | Οχι |
| 501 | Δ117 | Άγιος Αθανάσιος Β΄ | Β | Γ | Άγιος Αθανάσιος | 381 | 18 | | 6 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 502 | Δ118 | Λινόπετρα (ΔΡΑ.Σ.Ε.) | Β | Γ | Άγιος Αθανάσιος | 206 | 12 | | 3 | | 2 | | 1 | Οχι | | Ναι | Ναι |
| 503 | Δ119 | Άγιος Αμβρόσιος | Β | Γ | Άγιος Αμβρόσιος | 26 | 2 | | 0 | | 2 | | | Οχι | | Ναι | Οχι |
| 504 | Δ120 | Άγιος Τύχων | Β | Γ | Άγιος Τύχωνας | 91 | 6 | | 1 | | 0 | | | Οχι | | Ναι | Οχι |
| 505 | Δ121 | Αγρός - Νέαρχου Κληρίδη (Περιφερειακό) | Β | Γ | Αγρός | 56 | 3 | | 2 | | 1 | | 1 | Μέρος | 10/07/29 | Οχι | Οχι |
| 506 | Δ122 | Ακρωτήρι | Β | Γ | Ακωτήρι | 38 | 2 | | 2 | | 0 | | | Οχι | | Ναι | Οχι |
| 507 | Δ123 | Απεσιά (Περιφερειακό Ενιαίο Ολοήμερο) | Β | Γ | Απεσιά | 34 | | | 2 | | 1 | | | Οχι | | Ναι | Οχι |
| 508 | Δ124 | Ασγάτα | Β | Γ | Ασγάτα | 22 | 3 | | 0 | | 0 | | | Οχι | | Ναι | Οχι |
| 509 | Δ125 | Ασώματος | Β | Γ | Ασώματος | 38 | 2 | | 0 | | 1 | | 1 | Οχι | | Οχι | Οχι |
| 510 | Δ126 | Αυδήμου (Περιφερειακό) | Β | Γ | Αυδήμου | 65 | 5 | | 3 | | 0 | | | Οχι | | Οχι | Οχι |
| 511 | Δ127 | Αψιού (Περιφερειακό Ενιαίο Ολοήμερο) | Β | Γ | Αψιού | 18 | 3 | | 3 | | 0 | | 1 | Οχι | | Ναι | Οχι |
| 512 | Δ128 | Γερμασόγεια | Β | Γ | Γερμασόγεια | 365 | 12 | | 7 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 513 | Δ129 | Ποταμός Γερμασόγειας Α΄ (ΔΡΑ.Σ.Ε.) | Β | Γ | Ποταμός Γερμασόγειας | 256 | 12 | | 5 | | 3 | | | Οχι | | Ναι | Οχι |
| 514 | Δ130 | Ποταμός Γερμασόγειας Β΄ | Β | Γ | Ποταμός Γερμασόγειας | 459 | 18 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 515 | Δ131 | Επισκοπή | Β | Γ | Επισκοπή | 278 | 14 | | 5 | | 3 | | | Οχι | | Οχι | Οχι |
| 516 | Δ132 | Ερήμη (Ενιαίο Ολοήμερο) | Β | Γ | Ερήμη | 179 | 9 | | 4 | | 1 | | 1 | Οχι | | Ναι | Ναι |
| 517 | Δ133 | «Ιαματική» (Περιφερειακό Ενιαίο Ολοήμερο) | Β | Γ | Επταγώνεια | 60 | 3 | | 4 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 518 | Δ134 | Καλό Χωριό | Β | Γ | Καλό Χωριό Λεμεσού | 65 | | | 0 | | 1 | | | Οχι | | Ναι | Οχι |
| 519 | Δ135 | Κάτω Πολεμίδια Α΄ - Παναγίας Ευαγγελίστριας | Β | Γ | Κάτω Πολεμίδια | 218 | 11 | | 3 | | 0 | | | Μέρος | 08/12/26 | Ναι | Οχι |
| 520 | Δ136 | Κάτω Πολεμίδια Β΄ - Αγίου Γεωργίου | Β | Γ | Κάτω Πολεμίδια | 137 | 8 | | 5 | | 1 | | | Οχι | | Ναι | Οχι |
| 521 | Δ137 | Κάτω Πολεμίδια ΙΕ΄ (ΚΑ) - Αγίου Νεοφύτου | Β | Γ | Κάτω Πολεμίδια | 121 | | | | | 1 | | | Οχι | | Ναι | Οχι |
| 522 | Δ138 | Κάτω Πολεμίδια ΙΕ΄ (ΚΒ) - Αγίου Νεοφύτου | Β | Γ | Κάτω Πολεμίδια | 121 | 16 | | 7 | | | | 1 | Οχι | | Ναι | Οχι |
| 523 | Δ139 | Κάτω Πολεμίδια ΙΖ΄ - Αγίου Νικολάου | Β | Γ | Κάτω Πολεμίδια | 206 | 11 | | 6 | | 1 | | 1 | Οχι | | Οχι | Ναι |
| 524 | Δ140 | Κάτω Πολεμίδια ΚΔ΄ - Αποστόλου Βαρνάβα | Β | Γ | Κάτω Πολεμίδια | 212 | 11 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |

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| 525 | Δ141 | Κάτω Πολεμίδια ΚΗ΄ - Αρχαγγέλου Μιχαήλ | B | Γ | Κάτω Πολεμίδια | 306 | 12 | | 7 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 526 | Δ142 | Κιβίδες Πάνω | B | Γ | Πάνω Κιβίδες | 92 | 6 | | 3 | | 3 | | | Οχι | | Ναι | Οχι |
| 527 | Δ143 | Κολόσσι Α΄ - Αποστόλου Λουκά | B | Γ | Κολόσσι | 247 | 9 | | 4 | | 1 | | | Οχι | | Ναι | Οχι |
| 528 | Δ144 | Κολόσσι Β΄ - Αποστόλου Ανδρέα και Αγίας Φωτεινής | B | Γ | Κολόσσι | 184 | 11 | | 4 | | 0 | | 1 | Οχι | | Οχι | Οχι |
| 529 | Δ145 | Κυπερούντα (Περιφερειακό Ενιαίο Ολοήμερο) | B | Γ | Κυπερούντα | 61 | 6 | | 6 | | 3 | | | Ναι | 08/12/26 | Ναι | Οχι |
| 530 | Δ146 | Μουτταγιάκα | B | Γ | Μουτταγιάκα | 121 | 9 | | 4 | | 2 | | | Ναι | - | Ναι | Οχι |
| 531 | Δ147 | Παλόδεια | B | Γ | Παλόδεια | 97 | 2 | | 2 | | 1 | | | Ναι | 19/05/26 | Ναι | Οχι |
| 532 | Δ148 | Πάνω Πολεμίδια - Καρμιώτισσας | B | Γ | Πάνω Πολεμίδια | 256 | 16 | | 6 | | 1 | | | Οχι | | Ναι | Οχι |
| 533 | Δ149 | Παραμύθα - Σπιτάλι | B | Γ | Παραμύθα | 53 | 1 | | 0 | | 2 | | | Οχι | | Ναι | Οχι |
| 534 | Δ150 | Παρεκκλησιά | B | Γ | Παρεκκλησιά | 153 | 9 | | 3 | | 0 | | | Οχι | | Οχι | Οχι |
| 535 | Δ151 | Πάχνα | B | Γ | Πάχνα | 43 | 4 | | 4 | | 1 | | | Οχι | | Οχι | Οχι |
| 536 | Δ152 | Πελένδρι (ΕΟΣ) | B | Γ | Πελένδρι | 37 | 5 | | 3 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 537 | Δ153 | Πεντάκωμο | B | Γ | Πεντάκωμο | 38 | 3 | | 0 | | 1 | | | Οχι | | Οχι | Οχι |
| 538 | Δ154 | Πισσούρι | B | Γ | Πισσούρι | 70 | 6 | | 5 | | 0 | | 1 | Οχι | | Ναι | Οχι |
| 539 | Δ155 | Πύργος | B | Γ | Πύργος | 131 | 8 | | 3 | | 1 | | | Οχι | | Ναι | Οχι |
| 540 | Δ156 | Σούνι-Ζανακιά | B | Γ | Σούνι Ζανακιά | 19 | 2 | | 0 | | 1 | | | Οχι | | Ναι | Οχι |
| 541 | Δ157 | Τραχώνι Α΄ | B | Γ | Τραχώνι | 191 | 7 | | 4 | | 0 | | | Οχι | | Ναι | Οχι |
| 542 | Δ158 | Τραχώνι Β΄ | B | Γ | Τραχώνι | 116 | 6 | | 2 | | 0 | | 1 | Οχι | | Οχι | Οχι |
| 543 | Δ159 | Τριμήκληνη (Περιφερειακό Ενιαίο Ολοήμερο) | B | Γ | Τριμήκληνη | 105 | 6 | | 6 | | 1 | | | Οχι | | Ναι | Ναι |
| 544 | Δ160 | Ύψωνας Α΄ | B | Γ | Ύψωνας | 407 | 18 | | 3 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 545 | Δ161 | Ύψωνας Β΄ | B | Γ | Ύψωνας | 265 | 6 | | 5 | | 1 | | | Ναι | 02/12/29 | Ναι | Οχι |
| 546 | Δ162 | Ύψωνας Γ΄ | B | Γ | Ύψωνας | 309 | 13 | | 3 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 547 | Δ163 | Άγιος Δομέτιος Α΄ | B | A | Άγιος Δομέτιος | 131 | 8 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 548 | Δ164 | Άγιος Δομέτιος Β΄ (ΚΑ) | B | A | Άγιος Δομέτιος | 67 | 5 | | 1 | | 4 | | 1 | Οχι | | Ναι | Οχι |
| 549 | Δ165 | Άγιος Δομέτιος Β΄ (ΚΒ) | B | A | Άγιος Δομέτιος | 83 | 7 | | 5 | | 2 | | | Οχι | | Ναι | Οχι |
| 550 | Δ166 | Άγιος Δομέτιος Γ΄ | B | A | Άγιος Δομέτιος | 95 | 6 | | 5 | | | | 1 | Οχι | | Ναι | Οχι |
| 551 | Δ167 | Αγλαντζιά Α΄ - Αγίου Γεωργίου | B | A | Αγλαντζιά | 161 | 9 | | 5 | | 1 | | | Οχι | | Ναι | Οχι |
| 552 | Δ168 | Αγλαντζιά Γ΄ | B | A | Αγλαντζιά | 240 | 10 | | 3 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 553 | Δ169 | Αγλαντζιά Δ΄ (ΚΑ) | B | A | Αγλαντζιά | 195 | | | 1 | | 2 | | 1 | Ναι | 05/02/28 | Ναι | Οχι |
| 554 | Δ170 | Αγλαντζιά Δ΄ (ΚΒ) | B | A | Αγλαντζιά | 200 | 10 | | 3 | | 1 | | | Ναι | 05/02/28 | Ναι | Οχι |
| 555 | Δ171 | Αγλαντζιά Ε΄ - Άκη Κλεάνθους | B | A | Αγλαντζιά | 392 | 15 | | 6 | | | | 1 | Οχι | | Ναι | Ναι |
| 556 | Δ172 | Αγλαντζιά Στ΄ | B | A | Αγλαντζιά | 293 | 15 | | 5 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 557 | Δ173 | «Χατζηγεωργάκης Κορνέσιος» | B | A | Λευκωσία | 260 | 10 | | 3 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 558 | Δ174 | Έγκωμη Α΄ (ΚΑ) | B | A | Έγκωμη | 160 | 8 | | 2 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 559 | Δ175 | Έγκωμη Α΄ (ΚΒ) | B | A | Έγκωμη | 138 | 9 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 560 | Δ176 | Έγκωμη Β΄ | B | A | Έγκωμη | 203 | 8 | | 3 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 561 | Δ177 | Μακεδονίτισσα Α΄ | B | A | Έγκωμη | 321 | 14 | | 2 | | 1 | | 1 | Οχι | | Οχι | Οχι |
| 562 | Δ178 | Μακεδονίτισσα Β΄ | B | A | Έγκωμη | 288 | 14 | | 5 | | 2 | | 1 | Οχι | | Οχι | Οχι |
| 563 | Δ179 | Μακεδονίτισσα Γ΄ - Στυλιανού Λένα | B | A | Έγκωμη | 390 | 15 | | 7 | | 3 | | 1 | Οχι | | Ναι | Ναι |
| 564 | Δ180 | Άγιοι Ομολογητές (ΚΑ) | B | A | Λευκωσία | 127 | 6 | | 0 | | 2 | | | Οχι | | Ναι | Οχι |
| 565 | Δ181 | Άγιοι Ομολογητές (ΚΒ) | B | A | Λευκωσία | 136 | 6 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 566 | Δ182 | Άγιος Ανδρέας (ΚΑ) | B | A | Λευκωσία | 148 | 6 | | 0 | | | | 1 | Οχι | | Ναι | Οχι |
| 567 | Δ183 | Άγιος Ανδρέας (ΚΒ) | B | A | Λευκωσία | 130 | 6 | | 7 | | 1 | | | Οχι | | Ναι | Οχι |
| 568 | Δ184 | Άγιος Αντώνιος (ΔΡΑ.Σ.Ε.) | B | A | Λευκωσία | 124 | 8 | | 5 | | 1 | | | Οχι | | Ναι | Οχι |
| 569 | Δ185 | Άγιος Κασσιανός (ΔΡΑ.Σ.Ε.) | B | A | Λευκωσία | 42 | 5 | | 4 | | 3 | | | Οχι | | Οχι | Οχι |
| 570 | Δ186 | Ακρόπολη (ΚΑ) | B | A | Στρόβολος | 115 | 7 | | 1 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 571 | Δ187 | Ακρόπολη (ΚΒ) | B | A | Στρόβολος | 124 | 6 | | 7 | | 1 | | | Οχι | | Ναι | Οχι |
| 572 | Δ188 | Ελένειον (ΔΡΑ.Σ.Ε.) | B | A | Λευκωσία | 105 | 6 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 573 | Δ189 | Καϊμακλί Α΄ (ΚΑ) | B | A | Καϊμακλί | 117 | 8 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 574 | Δ190 | Καϊμακλί Β΄ (ΚΒ) | B | A | Καϊμακλί | 92 | 9 | | | | 1 | | | Οχι | | Ναι | Οχι |
| 575 | Δ191 | Καϊμακλί Γ΄ (ΚΑ) (ΔΡΑ.Σ.Ε.) | B | A | Καϊμακλί | 159 | | | | | | | | Οχι | | Ναι | Ναι |
| 576 | Δ192 | Καϊμακλί Γ΄ (ΚΒ) (ΔΡΑ.Σ.Ε.) | B | A | Καϊμακλί | 171 | 9 | | 5 | | | | 1 | Οχι | | Ναι | Ναι |
| 577 | Δ193 | Λυκαβηττός (ΚΑ) | B | A | Λευκωσία | 111 | 12 | | 7 | | 1 | | 1 | Οχι | | Ναι | Ναι |
| 578 | Δ194 | Λυκαβηττός (ΚΒ) | B | A | Λευκωσία | 114 | | | | | 1 | | | Οχι | | Ναι | Ναι |
| 579 | Δ195 | Παλουριώτισσα Α΄ (ΚΑ) (ΔΡΑ.Σ.Ε.) | B | A | Λευκωσία | 81 | 6 | | 1 | | | | | Ναι | - | Ναι | Οχι |
| 580 | Δ196 | Παλουριώτισσα Α΄ (ΚΒ) (ΔΡΑ.Σ.Ε.) | B | A | Λευκωσία | 103 | 6 | | 4 | | 1 | | 1 | Μέρος | - | Ναι | Οχι |
| 581 | Δ197 | Παλουριώτισσα Β΄ (ΚΑ) (ΔΡΑ.Σ.Ε.) | B | A | Λευκωσία | 98 | 6 | | | | | | | Οχι | | Ναι | Οχι |
| 582 | Δ198 | Παλουριώτισσα Β΄ (ΚΒ) (ΔΡΑ.Σ.Ε.) | B | A | Λευκωσία | 80 | 6 | | 3 | | | | 1 | Οχι | | Ναι | Οχι |
| 583 | Δ199 | Παλουριώτισσα Γ΄ | B | A | Λευκωσία | 181 | 10 | | | | 2 | | | Οχι | | Οχι | Οχι |
| 584 | Δ200 | Φανερωμένη (ΔΡΑ.Σ.Ε.) | B | A | Λευκωσία | 66 | 5 | | 2 | | | | 1 | Οχι | | Ναι | Οχι |
| 585 | Δ201 | Αγία Μαρίνα (ΚΑ) | B | A | Στρόβολος | 110 | 6 | | | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 586 | Δ202 | Αγία Μαρίνα (ΚΒ) | B | A | Στρόβολος | 95 | 6 | | 4 | | | | | Οχι | | Ναι | Οχι |
| 587 | Δ203 | Άγιος Βασίλειος (ΚΑ) | B | A | Στρόβολος | 218 | 12 | | 2 | | 1 | | | Οχι | | Οχι | Ναι |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 588 | Δ204 | Άγιος Βασίλειος (ΚΒ) | Β | Α | Στρόβολος | 211 | 10 | | 6 | | 1 | | | Οχι | | Οχι | Ναι |
| 589 | Δ205 | Άγιος Δημήτριος | Β | Α | Στρόβολος | 297 | 12 | | 6 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 590 | Δ206 | Άγιος Σπυρίδωνας (ΔΡΑ.Σ.Ε.) | Β | Α | Στρόβολος | 124 | 8 | | 5 | | 1 | | | Οχι | | Ναι | Οχι |
| 591 | Δ207 | Απόστολος Βαρνάβας | Β | Α | Στρόβολος | 211 | 12 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 592 | Δ208 | Απόστολος Λουκάς | Β | Α | Στρόβολος | 239 | 13 | | 6 | | 2 | | 1 | Οχι | | Οχι | Οχι |
| 593 | Δ209 | Αρχάγγελος | Β | Α | Στρόβολος | 272 | 13 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 594 | Δ210 | Δασούπολη (ΚΑ) | Β | Α | Στρόβολος | 177 | 9 | | 3 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 595 | Δ211 | Δασούπολη (ΚΒ) | Β | Α | Στρόβολος | 189 | 9 | | 4 | | 1 | | | Οχι | | Ναι | Οχι |
| 596 | Δ212 | Κωνσταντινουπόλεως | Β | Α | Λευκωσία | 297 | 15 | | 7 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 597 | Δ213 | Περνέρα | Β | Α | Στρόβολος | 318 | 15 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 598 | Δ214 | «Πεύκιος Γεωργιάδης» (Ενιαίο Ολοήμερο) | Β | Α | Στρόβολος | 243 | 15 | | 7 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 599 | Δ215 | Σταυρός (ΚΑ) | Β | Α | Στρόβολος | 138 | 17 | | 4 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 600 | Δ216 | Σταυρός (ΚΒ) | Β | Α | Στρόβολος | 149 | | | | | 4 | | | Οχι | | Ναι | Οχι |
| 601 | Δ217 | Χρυσελεούσα (ΚΑ) | Β | Α | Στρόβολος | 138 | 6 | | 3 | | | | 1 | Οχι | | Οχι | Οχι |
| 602 | Δ218 | Χρυσελεούσα (ΚΒ) | Β | Α | Στρόβολος | 151 | 7 | | 1 | | 3 | | | Οχι | | Οχι | Οχι |
| 603 | Δ219 | Αγία Βαρβάρα | Β | Α | Αγία Βαρβάρα | 207 | 9 | | 4 | | | | | Οχι | | Ναι | Οχι |
| 604 | Δ220 | Αγία Μαρίνα Ξυλιάτου | Β | Α | Αγία Μαρίνα Ξυλιάτου | 13 | 3 | | 4 | | | | | Οχι | | Ναι | Οχι |
| 605 | Δ221 | Αγίοι Τριμιθιάς | Β | Α | Άγιοι Τριμιθιάς | 151 | 7 | | 3 | | 1 | | | Οχι | | Ναι | Οχι |
| 606 | Δ222 | Άγιος Επιφάνιος | Β | Α | Άγιος Επιφάνιος | 30 | 1 | | 1 | | 1 | | | Οχι | | Οχι | Οχι |
| 607 | Δ223 | Άγιος Ιωάννης Λευκωσίας | Β | Α | Λευκωσία | 20 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 608 | Δ224 | Άγιος Μάρωνας | Β | Α | Λακατάμεια | 75 | 6 | | 5 | | | | 1 | Οχι | | Ναι | Οχι |
| 609 | Δ225 | Αγροκηπιά | Β | Α | Αγροκηπιά | 33 | 3 | | 1 | | 1 | | | Οχι | | Οχι | Οχι |
| 610 | Δ226 | Ακάκι | Β | Α | Ακάκι | 178 | 10 | | 7 | | | | | Οχι | | Ναι | Οχι |
| 611 | Δ227 | Αλάμπρα | Β | Α | Αλάμπρα | 93 | 6 | | 3 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 612 | Δ228 | Ανάγεια | Β | Α | Ανάγεια | 85 | 6 | | 2 | | | | | Οχι | | Οχι | Οχι |
| 613 | Δ229 | Αναλιόντας | Β | Α | Αναλιόντα | 23 | 2 | | | | 1 | | | Οχι | | Οχι | Οχι |
| 614 | Δ230 | Ανθούπολη (ΚΑ) | Β | Α | Λακατάμεια | 163 | 8 | | 1 | | | | 1 | Οχι | | Ναι | Οχι |
| 615 | Δ231 | Ανθούπολη (ΚΒ) | Β | Α | Λακατάμεια | 103 | 7 | | 6 | | 2 | | | Οχι | | Ναι | Οχι |
| 616 | Δ232 | Αρεδιού | Β | Α | Αρεδιού | 96 | 6 | | 2 | | 1 | | | Οχι | | Οχι | Οχι |
| 617 | Δ233 | Ασίνου (Περιφερειακό) | Β | Α | Νικητάρι | 85 | 6 | | 4 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 618 | Δ234 | Αστρομερίτης | Β | Α | Αστρομερίτης | 100 | 6 | | 6 | | 2 | | | Οχι | | Ναι | Οχι |
| 619 | Δ235 | Γέρι Α΄ | Β | Α | Γέρι | 243 | 12 | | 4 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 620 | Δ236 | Γέρι Β΄ | Β | Α | Γέρι | 278 | 10 | | 4 | | 1 | | | Ναι | 07/12/29 | Ναι | Οχι |
| 621 | Δ237 | Δάλι Α΄ | Β | Α | Δάλι | 207 | 12 | | 4 | | 3 | | | Μέρος | 24/01/27 | Ναι | Οχι |
| 622 | Δ238 | Δάλι Β΄ | Β | Α | Δάλι | 242 | | | | | 1 | | | Οχι | | Ναι | Οχι |
| 623 | Δ239 | Δάλι Γ΄ | Β | Α | Δάλι | 441 | 18 | | 5 | | | | 1 | Οχι | | Ναι | Οχι |
| 624 | Δ240 | Δένεια | Β | Α | Δένεια | 24 | 3 | | 1 | | 4 | | | Οχι | | Οχι | Οχι |
| 625 | Δ241 | Δευτερά Πάνω | Β | Α | Πάνω Δευτερά | 274 | 13 | | 4 | | 1 | | | Οχι | | Ναι | Οχι |
| 626 | Δ242 | Εργάτες | Β | Α | Εργάτες | 90 | 5 | | 3 | | 3 | | | Οχι | | Ναι | Οχι |
| 627 | Δ243 | Ευρύχου | Β | Α | Ευρύχου | 92 | 6 | | 4 | | 3 | | | Οχι | | Ναι | Οχι |
| 628 | Δ244 | Κακοπετριά | Β | Α | Καποπετριά | 117 | | | | | 2 | | | Οχι | | Ναι | Οχι |
| 629 | Δ245 | Καλό Χωριό Ορεινής | Β | Α | Καλό Χωριό Ορεινής | 41 | 3 | | | | | | | Οχι | | Οχι | Οχι |
| 630 | Δ246 | Καμπιά - Εθνομάρτυρα Κυπριανού | Β | Α | Καμπιά | 19 | 1 | | | | 1 | | | Οχι | | Οχι | Οχι |
| 631 | Δ247 | Κάμπος | Β | Α | Κάμπος | 5 | | | | | 1 | | | Οχι | | Ναι | Οχι |
| 632 | Δ248 | Καπέδες (ΕΟΣ) | Β | Α | Καπέδες | 33 | 4 | | 2 | | | | | Οχι | | Οχι | Οχι |
| 633 | Δ249 | Κλήρου | Β | Α | Κλήρου | 135 | 6 | | 1 | | | | | Οχι | | Οχι | Οχι |
| 634 | Δ250 | Κοκκινοτριμιθιά Α΄ | Β | Α | Κοκκινοτριμιθιά | 151 | 7 | | 3 | | 2 | | | Οχι | | Ναι | Οχι |
| 635 | Δ251 | Κοκκινοτριμιθιά Β΄ | Β | Α | Κοκκινοτριμιθιά | 194 | 15 | | 2 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 636 | Δ252 | Κοράκου | Β | Α | Κοράκου | 30 | 5 | | 1 | | 1 | | | Οχι | | Ναι | Οχι |
| 637 | Δ253 | Λακατάμεια Α΄ (ΚΑ) - Αγίας Παρασκευής και Αγίου Νικολάου | Β | Α | Λακατάμεια | 136 | 3 | | | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 638 | Δ254 | Λακατάμεια Α΄ (ΚΒ) - Αγίας Παρασκευής και Αγίου Νικολάου | Β | Α | Λακατάμεια | 200 | 8 | | 3 | | | | | Οχι | | Ναι | Οχι |
| 639 | Δ255 | Λακατάμεια Β΄ - Αγίου Μάμα | Β | Α | Λακατάμεια | 241 | 13 | | 6 | | 2 | | | Οχι | | Ναι | Ναι |
| 640 | Δ256 | Λακατάμεια Γ΄ - Αγίου Γεωργίου | Β | Α | Λακατάμεια | 364 | 17 | | 3 | | 4 | | 1 | Οχι | | Ναι | Οχι |
| 641 | Δ257 | Λακατάμεια Δ΄ - Αγίου Νεοφύτου | Β | Α | Λακατάμεια | 270 | 12 | | 5 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 642 | Δ258 | Λακατάμεια Ε΄ - Αγίου Ιωάννη Χρυσοστόμου | Β | Α | Λακατάμεια | 351 | 15 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 643 | Δ259 | Λακατάμεια Στ΄ - Αγίου Στυλιανού | Β | Α | Λακατάμεια | 315 | 16 | | 4 | | 4 | | 1 | Οχι | | Ναι | Οχι |
| 644 | Δ260 | Λακατάμεια Ζ΄- Αγίου Παντελεήμονα | Β | Α | Λακατάμεια | 327 | 18 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 645 | Δ261 | Λατσιά Α΄ | Β | Α | Λατσιά | 242 | 13 | | 3 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 646 | Δ262 | Λατσιά Β΄ (ΚΑ) | Β | Α | Λατσιά | 131 | 6 | | 3 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 647 | Δ263 | Λατσιά Β΄ (ΚΒ) | Β | Α | Λατσιά | 145 | 4 | | 3 | | 2 | | | Οχι | | Ναι | Οχι |
| 648 | Δ264 | Λατσιά Γ΄ | Β | Α | Λατσιά | 281 | 14 | | 4 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 649 | Δ265 | Λατσιά Δ΄ | Β | Α | Λατσιά | 286 | 14 | | 7 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 650 | Δ266 | Λυθροδόντας - «Μελέτιον» | Β | Α | Λυθροδόντας | 245 | 13 | | 4 | | 3 | | | Οχι | | Ναι | Οχι |
| 651 | Δ267 | Λύμπια | Β | Α | Λύμπια | 208 | 12 | | 5 | | 3 | | | Οχι | | Ναι | Οχι |
| 652 | Δ268 | Μαθιάτης | Β | Α | Μαθιάτης | 46 | 5 | | 3 | | 2 | | | Οχι | | Ναι | Οχι |
| 653 | Δ269 | Μάμμαρη | Β | Α | Μάμμαρη | 146 | 7 | | 3 | | | | | Οχι | | Ναι | Οχι |
| 654 | Δ270 | Μένικο | Β | Α | Μένικο | 72 | 6 | | 2 | | 1 | | | Οχι | | Οχι | Οχι |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 655 | Δ271 | Μιτσερό | Β | Α | Μιτσερό | 54 | 5 | | 2 | | | | 1 | Οχι | | Ναι | Οχι |
| 656 | Δ272 | Ορούντα | Β | Α | Ορούντα | 24 | 3 | | | | 1 | | | Οχι | | Οχι | Οχι |
| 657 | Δ273 | Παλαιομέτοχο Α΄ | Β | Α | Παλαιομέτοχο | 146 | 11 | | 6 | | | | | Οχι | | Ναι | Οχι |
| 658 | Δ274 | Παλαιομέτοχο Β΄ | Β | Α | Παλαιομέτοχο | 90 | 8 | | 4 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 659 | Δ275 | Παλαιχώρι (Περιφερειακό Ενιαίο Ολοήμερο) | Β | Α | Παλαιχώρι Μόρφου | 53 | 6 | | 5 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 660 | Δ276 | Πέρα Χωριό Νήσου Α΄ | Β | Α | Πέρα Χωριό Νήσου | 226 | | | | | 1 | | | Οχι | | Ναι | Οχι |
| 661 | Δ277 | Πέρα Χωριό Νήσου Β΄ | Β | Α | Πέρα Χωριό Νήσου | 148 | 7 | | 4 | | | | 1 | Οχι | | Ναι | Ναι |
| 662 | Δ278 | Περιστερώνα | Β | Α | Περιστερώνα | 139 | 9 | | 4 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 663 | Δ279 | Ποταμιά | Β | Α | Ποταμιά | 42 | 3 | | 1 | | 2 | | | Οχι | | Οχι | Οχι |
| 664 | Δ280 | Πύργος Κάτω | Β | Α | Πύργος Κάτω | 34 | 6 | | 2 | | 1 | | | Οχι | | Ναι | Οχι |
| 665 | Δ281 | Σια | Β | Α | Σια | 56 | | | | | 1 | | | Οχι | | Ναι | Οχι |
| 666 | Δ282 | Ταμασός (Περιφερειακό) | Β | Α | Πέρα Ορεινής | 138 | 8 | | 4 | | | | | Οχι | | Ναι | Οχι |
| 667 | Δ283 | Τσέρι Α΄ | Β | Α | Τσέρι | 277 | 12 | | 4 | | 3 | | 1 | Οχι | | Ναι | Οχι |
| 668 | Δ284 | Τσέρι Β΄ | Β | Α | Τσέρι | 203 | 12 | | 3 | | 2 | | 1 | Οχι | | Οχι | Οχι |
| 669 | Δ285 | Φαρμακάς - Καμπί | Β | Α | Φαρμακάς | 34 | 1 | | 1 | | 2 | | | Οχι | | Ναι | Οχι |
| 670 | Δ286 | Ψιμολόφου | Β | Α | Ψιμολόφου | 144 | 6 | | 2 | | | | | Οχι | | Οχι | Οχι |
| 671 | Δ287 | Πάφος Α΄- Νεοφύτειο | Β | Ε | Πάφος | 147 | 6 | | 3 | | 1 | | | Οχι | | Οχι | Οχι |
| 672 | Δ288 | Πάφος Β΄- Δημήτρειο | Β | Ε | Πάφος | 152 | 8 | | 2 | | | | | Οχι | | Ναι | Οχι |
| 673 | Δ289 | Πάφος Γ΄ (ΚΑ) - Αποστόλου Παύλου (ΔΡΑ.Σ.Ε.) | Β | Ε | Πάφος | 103 | 6 | | 1 | | | | 1 | Οχι | | Ναι | Οχι |
| 674 | Δ290 | Πάφος Γ΄ (ΚΒ) - Αποστόλου Παύλου (ΔΡΑ.Σ.Ε.) | Β | Ε | Πάφος | 124 | | | 2 | | 4 | | | Οχι | | Ναι | Οχι |
| 675 | Δ291 | Πάφος Δ΄ - Κάτω Περβολιών (ΔΡΑ.Σ.Ε.) | Β | Ε | Πάφος | 341 | 14 | | 5 | | | | | Οχι | | Ναι | Οχι |
| 676 | Δ292 | Πάφος Ε΄ - Αγίου Δημητρίου | Β | Ε | Πάφος | 112 | 9 | | 6 | | | | 1 | Ναι | 09/11/24 | Ναι | Οχι |
| 677 | Δ293 | Πάφος Στ΄ - Κάτω Πάφου (ΔΡΑ.Σ.Ε.) | Β | Ε | Πάφος | 263 | | | | | 2 | | | Οχι | | Ναι | Οχι |
| 678 | Δ294 | Πάφος Ζ΄ - Αγίου Κενδέα (ΔΡΑ.Σ.Ε.) | Β | Ε | Πάφος | 179 | 10 | | 3 | | | | | Οχι | | Ναι | Οχι |
| 679 | Δ295 | Πάφος Η΄ - Ιορδάνειο | Β | Ε | Πάφος | 289 | 12 | | 5 | | 1 | | | Οχι | | Ναι | Οχι |
| 680 | Δ296 | Πάφος Θ΄ - Κουπάτειο | Β | Ε | Πάφος | 413 | 18 | | 4 | | 2 | | 1 | Οχι | | Οχι | Οχι |
| 681 | Δ297 | Πάφος Ι΄ - «Ευαγόρας Παλληκαρίδης» | Β | Ε | Πάφος | 399 | 17 | | 7 | | 1 | | | Οχι | | Ναι | Οχι |
| 682 | Δ298 | Πάφος ΙΑ΄ - Αγίου Σπυρίδωνα | Β | Ε | Πάφος | 284 | 12 | | 5 | | 2 | | 1 | Οχι | | Ναι | Οχι |
| 683 | Δ299 | Πάφος ΙΒ΄- «Πεύκιος Γεωργιάδης» | Β | Ε | Πάφος | 272 | 12 | | 7 | | 4 | | 1 | Οχι | | Ναι | Ναι |
| 684 | Δ300 | Πάφος ΙΓ΄ (ΔΡΑ.Σ.Ε.) | Β | Ε | Πάφος | 260 | 12 | | 6 | | | | 1 | Οχι | | Ναι | Ναι |
| 685 | Δ301 | Αγία Μαρίνα Χρυσοχούς | Β | Ε | Αγία Μαρίνα Χρυσοχούς | 58 | 6 | | 3 | | 3 | | | Οχι | | Ναι | Οχι |
| 686 | Δ302 | Αναρίτα | Β | Ε | Αναρίτα | 24 | 3 | | | | 1 | | | Οχι | | Ναι | Οχι |
| 687 | Δ303 | Αργάκα | Β | Ε | Αργάκα Πάνω | 89 | 7 | | 4 | | | | 1 | Οχι | | Ναι | Οχι |
| 688 | Δ304 | Γεροσκήπου Α΄ | Β | Ε | Γεροσκήπου | 289 | 12 | | 7 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 689 | Δ305 | Γεροσκήπου Β΄ (ΔΡΑ.Σ.Ε.) | Β | Ε | Γεροσκήπου | 329 | 15 | | 5 | | 2 | | 1 | Οχι | | Ναι | Ναι |
| 690 | Δ306 | Γιόλου (Περιφερειακό Ενιαίο Ολοήμερο) | Β | Ε | Γιόλου | 69 | 6 | | 5 | | 3 | | | Οχι | | Ναι | Οχι |
| 691 | Δ307 | Δρούσεια | Β | Ε | Δρούσεια | 51 | 2 | | 1 | | 1 | | | Οχι | | Ναι | Οχι |
| 692 | Δ308 | Έμπα | Β | Ε | Έμπα | 256 | 12 | | 3 | | 2 | | | Οχι | | Ναι | Οχι |
| 693 | Δ309 | Ίνεια | Β | Ε | Ίνεια | 15 | 3 | | 1 | | 1 | | | Οχι | | Ναι | Οχι |
| 694 | Δ310 | Κισσόνεργα - Χρίστου Κκέλη | Β | Ε | Κισσόνεργα | 136 | 5 | | 4 | | 1 | | | Οχι | | Οχι | Οχι |
| 695 | Δ311 | Κονιά | Β | Ε | Κονιά | 207 | 12 | | 3 | | | | | Οχι | | Ναι | Οχι |
| 696 | Δ312 | Κούκλια | Β | Ε | Κούκλια | 44 | 5 | | | | 2 | | | Οχι | | Οχι | Οχι |
| 697 | Δ313 | Μανδριά | Β | Ε | Μανδριά | 61 | 3 | | 1 | | | | | Οχι | | Ναι | Οχι |
| 698 | Δ314 | Μεσόγη | Β | Ε | Μεσόγη | 177 | 9 | | 4 | | 1 | | | Οχι | | Ναι | Οχι |
| 699 | Δ315 | Παναγιά | Β | Ε | Παναγιά | 10 | 3 | | | | 1 | | | Οχι | | Ναι | Οχι |
| 700 | Δ316 | Πέγεια | Β | Ε | Πέγεια | 226 | 11 | | 3 | | | | 1 | Οχι | | Ναι | Οχι |
| 701 | Δ317 | Πολέμι | Β | Ε | Πολέμι | 105 | 7 | | 4 | | 1 | | | Οχι | | Ναι | Οχι |
| 702 | Δ318 | Πόλη Χρυσοχούς (ΔΡΑ.Σ.Ε.) | Β | Ε | Πόλη Χρυσοχούς | 300 | 18 | | 6 | | 1 | | 1 | Οχι | | Ναι | Ναι |
| 703 | Δ319 | Πομός | Β | Ε | Πομός | 13 | 3 | | | | 3 | | | Οχι | | Οχι | Οχι |
| 704 | Δ320 | Στρουμπί | Β | Ε | Στρουμπί | 31 | 3 | | | | | | | Οχι | | Ναι | Οχι |
| 705 | Δ321 | Τάλα | Β | Ε | Τάλα | 78 | 6 | | 3 | | | | | Οχι | | Ναι | Οχι |
| 706 | Δ322 | Τίμη (Περιφερειακό) | Β | Ε | Τίμη | 90 | 6 | | 2 | | 1 | | | Ναι | - | Ναι | Οχι |
| 707 | Δ323 | Τρεμιθούσα | Β | Ε | Τρεμιθούσα | 44 | 2 | | | | | | | Οχι | | Οχι | Οχι |
| 708 | Δ324 | Τσάδα - Κοίλη «Ευαγόρα Παλληκαρίδη» (Περιφερειακό) | Β | Ε | Τσάδα | 77 | 4 | | 1 | | 1 | | 1 | Οχι | | Ναι | Οχι |
| 709 | Δ325 | Χλώρακας - Αγίου Νικολάου (ΔΡΑ.Σ.Ε.) | Β | Ε | Χλώρακας | 250 | 9 | | 3 | | | | | Οχι | | Οχι | Οχι |
| 710 | Δ326 | Χλώρακας-Λέμπα- Αγίου Στεφάνου (ΔΡΑ.Σ.Ε.) | Β | Ε | Λέμπα | 295 | 11 | | 4 | | 1 | | 1 | Οχι | | Ναι | Ναι |
| 711 | Δ327 | Χολέτρια | Β | Ε | Χολέτρια | 22 | 1 | | 3 | | 2 | | | Οχι | | Ναι | Οχι |
| 712 | Τ1 | Α ΤΕΣΕΚ ΛΕΥΚΩΣΙΑΣ | Δ | Α | Λευκωσία | 483 | 13 | | 36 | | 17 | 5 | | Οχι | | Ναι | Οχι |

| | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 713 | T2 | Β ΤΕΣΕΚ ΛΕΥΚΩΣΙΑΣ | Δ | Α | Λευκωσία | 154 | 7 | | 13 | | 2 | 1 | | Οχι | | Οχι | Οχι |
| 714 | T3 | ΤΕΧΝΙΚΗ ΣΧΟΛΗ ΜΑΚΑΡΙΟΣ Γ' | Δ | Α | Λευκωσία | 734 | 19 | | 15 | | 26 | 4 | | Οχι | | Ναι | Οχι |
| 715 | T4 | Α ΤΕΣΕΚ ΛΕΜΕΣΟΥ | Δ | Γ | Λεμεσός | 378 | 13 | | 22 | | 17 | 6 | | Οχι | | Οχι | Οχι |
| 716 | T5 | Β΄ ΤΕΣΕΚ ΓΡΗΓΟΡΗ ΑΥΞΕΝΤΙΟΥ ΛΕΜΕΣΟΥ | Δ | Γ | Λεμεσός | 346 | 8 | | 23 | | 11 | 3 | | Ναι | - | Οχι | Οχι |
| 717 | T6 | Γ' ΤΕΣΕΚ ΛΕΜΕΣΟΥ | Δ | Γ | Λεμεσός | 418 | | | | | | | | Οχι | | Ναι | Οχι |
| 718 | T7 | ΤΕΣΕΚ ΑΓΙΟΥ ΛΑΖΑΡΟΥ ΛΑΡΝΑΚΑΣ | Δ | Β | Λάρνακα | 239 | 11 | | 20 | | 10 | 5 | | Οχι | | Οχι | Οχι |
| 719 | T8 | ΤΕΧΝΙΚΗ ΣΧΟΛΗ ΛΑΡΝΑΚΑΣ | Δ | Β | Λάρνακα | 500 | 16 | | 28 | | 6 | 4 | | Οχι | | Ναι | Οχι |
| 720 | T9 | ΠΕΡΙΦΕΡΕΙΑΚΗ ΓΕΩΡΓΙΚΗ ΤΕΧΝΙΚΗ & ΕΠΑΓΓΕΛΜΑΤΙΚΗ ΣΧΟΛΗ ΕΚΠΑΙΔΕΥΣΗΣ ΚΑΙ ΚΑΤΑΡΤΗΣΗΣ ΑΜΜΟΧΩΣΤΟΥ / ΑΥΓΟΡΟΥ | Δ | Δ | Αυγόρου | 328 | | | 10 | | 10 | 6 | | Οχι | | Ναι | Οχι |
| 721 | T10 | Τ.Ε.Σ.Ε.Κ ΠΑΡΑΛΙΜΝΙΟΥ | Δ | Δ | Παραλίμνι | 254 | 1 | | 9 | | 11 | 3 | | Οχι | | Οχι | Οχι |
| 722 | T11 | ΤΕΣΕΚ ΠΑΦΟΥ | Δ | Ε | Πάφος | 630 | 18 | | 28 | | 11 | 2 | | Οχι | | Ναι | Οχι |
| 723 | T12 | ΛΥΚΕΙΟ ΚΑΙ ΤΕΣΕΚ ΠΟΛΕΩΣ ΧΡΥΣΟΧΟΥΣ | Δ | Ε | Πόλη Χρυσοχούς | 91 | 17 | | 9 | | 1 | 1 | | Οχι | | Ναι | Οχι |
| 724 | T13 | ΑΠΕΗΤΕΙΟ ΓΥΜΝΑΣΙΟ ΑΓΡΟΥ | Δ | Γ | Αγρός | 30 | | | | | | | | Οχι | | Ναι | Οχι |
| 725 | T14 | ΛΥΚΕΙΟ ΚΑΙ ΤΕΣΕΚ ΑΓ. ΧΑΡΑΛΑΜΠΟΥΣ ΕΜΠΑΣ | Δ | Ε | Έμπα | 64 | | | | | | | | Οχι | | Ναι | Οχι |
| 726 | T15 | ΣΧΟΛΗ ΟΜΟΔΟΥΣ | Δ | Γ | Λεμεσός | 9 | | | | | | | | Οχι | | Ναι | Οχι |

## Appendix H: Data of techno-economic analysis

Maintenance and repair of the reference building

| Whole Building | | | |
|---|---|---|---|
| **Reference** | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 100 | € 100.00 |
| **Shading Maintenance** | 0 | | € 0.00 |
| **MVHR Maintenance** | 0 | | € 0.00 |
| **Ventilator Maintenance** | 0 | | € 0.00 |
| **Total** | - | - | **€ 190.00** |

| Wall system repair (every 5 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| Roof repair (every 20 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Roof Maintenance** | 84.05 | 11 | € 924.55 |

Investment cost, maintenance and repair of the wall renovation

| Whole Building | | | |
|---|---|---|---|
| **Wall renovation** | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 100 | € 100.00 |
| **Shading Maintenance** | 0 | | € 0.00 |
| **MVHR Maintenance** | 0 | | € 0.00 |
| **Ventilator Maintenance** | 0 | | € 0.00 |
| **Total** | - | - | **€ 190.00** |

| Wall system repair (every 15 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| Roof repair (every 20 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Roof Maintenance** | 84.05 | 11 | € 924.55 |

| Investment cost - Wall | | | |
|---|---|---|---|
| **Case 1= 5 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall system** | 32.6 | 38 | € 1,238.80 |
| **Insulation around windows** | 6.6 | 23 | € 151.80 |
| | | | **€ 1,390.60** |

| Investment cost - Wall | | | |
|---|---|---|---|
| **Case 2=8 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall system** | 32.6 | 42 | € 1,369.20 |
| **Insulation around windows** | 6.6 | 23 | € 151.80 |
| | | | **€ 1,521.00** |

| Investment cost - Wall | | | |
|---|---|---|---|
| **Case 3=10 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall system** | 32.6 | 45 | € 1,467.00 |
| **Insulation around windows** | 6.6 | 23 | € 151.80 |
| | | | **€ 1,618.80** |

| Investment cost - Wall | | | |
|---|---|---|---|
| **Case 4=15 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall system** | 32.6 | 50 | € 1,630.00 |
| **Insulation around windows** | 6.6 | 23 | € 151.80 |
| | | | **€ 1,781.80** |

Investment cost, maintenance and repair of the roof renovation

| Whole Building | | | |
|---|---|---|---|
| **Roof renovation** | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 100 | € 100.00 |
| **Shading Maintenance** | 0 | | € 0.00 |
| **MVHR Maintenance** | 0 | | € 0.00 |
| **Ventilator Maintenance** | 0 | | € 0.00 |
| **Total** | - | - | **€ 190.00** |

| Wall system repair (every 5 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| Investment cost- Roof | | | |
|---|---|---|---|
| **Case 5= 5 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Primer** | 84 | 8 | € 672.00 |
| **Insulation** | 84 | 10 | € 840.00 |
| **Paving slabs** | 84 | 18 | € 1,512.00 |
| | | | **€ 3,024.00** |

| Investment cost- Roof | | | |
|---|---|---|---|
| **Case 6=10 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Primer** | 84 | 8 | € 672.00 |
| **Insulation** | 84 | 15 | € 1,260.00 |
| **Paving slabs** | 84 | 18 | € 1,512.00 |
| | | | **€ 3,444.00** |

| Investment cost- Roof | | | |
|---|---|---|---|
| **Case 7=15 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Primer** | 84 | 8 | € 672.00 |
| **Insulation** | 84 | 20 | € 1,680.00 |
| **Paving slabs** | 84 | 18 | € 1,512.00 |
| | | | **€ 3,864.00** |

| Investment cost- Roof | | | |
|---|---|---|---|
| **Case 8=20 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Primer** | 84 | 8 | € 672.00 |
| **Insulation** | 84 | 25 | € 2,100.00 |
| **Paving slabs** | 84 | 18 | € 1,512.00 |
| | | | **€ 4,284.00** |

Investment cost, maintenance and repair of the ground floor renovation

| Whole Building | | | |
|---|---|---|---|
| **Floor renovation** | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 100 | € 100.00 |
| **Shading Maintenance** | 0 | | € 0.00 |
| **MVHR Maintenance** | 0 | | € 0.00 |
| **Ventilator Maintenance** | 0 | | € 0.00 |
| **Total** | - | - | **€ 190.00** |

| Wall system repair (every 5 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |

| | | | |
|---|---|---|---|
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| **Roof repair (every 20 years)** | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Roof Maintenance** | 84.05 | 11 | € 924.55 |

| **Investment cost- Floor** | | | |
|---|---|---|---|
| **Case 9= 5 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Insulation** | 56 | 10 | € 560.00 |
| **Screed** | 56 | 13 | € 728.00 |
| **Final floor** | 56 | 45 | € 2,520.00 |
| | | | **€ 3,808.00** |

| **Investment cost- Floor** | | | |
|---|---|---|---|
| **Case 10= 8 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Insulation** | 56 | 12 | € 672.00 |
| **Screed** | 56 | 13 | € 728.00 |
| **Final floor** | 56 | 45 | € 2,520.00 |
| | | | **€ 3,920.00** |

| **Investment cost- Floor** | | | |
|---|---|---|---|
| **Case 11= 10 cm** | | | |
| **Component** | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Insulation** | 56 | 15 | € 840.00 |
| **Screed** | 56 | 13 | € 728.00 |
| **Final floor** | 56 | 45 | € 2,520.00 |
| | | | **€ 4,088.00** |

Investment cost, maintenance and repair of the energy efficient windows

| **Whole Building** | | | |
|---|---|---|---|
| **Window replacement** | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 50 | € 50.00 |
| **Shading Maintenance** | 0 | | € 0.00 |
| **MVHR Maintenance** | 0 | | € 0.00 |
| **Ventilator Maintenance** | 0 | | € 0.00 |
| **Total** | - | - | **€ 140.00** |

| **Wall system repair (every 5 years)** | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€$m^2$) | Cost (€) |
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| Roof repair (every 20 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€$m^2$) | Cost (€) |
| **Roof Maintenance** | 84.05 | 11 | € 924.55 |

| Investment cost - Windows | | | |
|---|---|---|---|
| Case 12= double with standard frame | | | |
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **window** | 16.6 | 200 | € 3,320.00 |

| Investment cost - Windows | | | |
|---|---|---|---|
| Case 13= double with insulated frame no.1 | | | |
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **window** | 16.6 | 250 | € 4,150.00 |

| Investment cost - Windows | | | |
|---|---|---|---|
| Case 14= double with insulated frame no.2 | | | |
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **window** | 16.6 | 300 | € 4,980.00 |

| Investment cost - Windows | | | |
|---|---|---|---|
| Case 15= triple with insulated frame | | | |
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **window** | 16.6 | 350 | € 5,810.00 |

Investment cost, maintenance and repair of the ventilator system

| Whole Building | | | |
|---|---|---|---|
| Ventilator | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 100 | € 100.00 |
| **Shading Maintenance** | 0 | | € 0.00 |
| **MVHR Maintenance** | 0 | | € 0.00 |
| **Ventilator Maintenance** | 1 | 40 | € 40.00 |
| **Total** | - | - | **€ 230.00** |

| Wall system repair (every 5 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| Roof repair (every 20 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Roof Maintenance** | 84.05 | 11 | € 924.55 |

| Investment cost - Ventilation | | | |
|---|---|---|---|
| Case 17 | | | |
| | Item | Cost (€) | Cost (€) |
| **Ventilator System** | 1 | 1000 | € 1,000.00 |

| Investment cost - Ventilation | | | |
|---|---|---|---|
| Case 18 | | | |
| | Item | Cost (€) | Cost (€) |
| **Ventilator System** | 1 | 1000 | € 1,000.00 |

Investment cost, maintenance and repair of the fixed shutter system

| Whole Building | | | |
|---|---|---|---|
| Shading | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 100 | € 100.00 |
| **Shading Maintenance** | 1 | 50 | € 50.00 |
| **MVHR Maintenance** | 0 | | € 0.00 |
| **Ventilator Maintenance** | 0 | | € 0.00 |
| **Total** | - | - | **€ 240.00** |

| Wall system repair (every 5 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| Roof repair (every 20 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Roof Maintenance** | 84.05 | 11 | € 924.55 |

| Investment cost - Shading system | | | |
|---|---|---|---|
| Case 20: fixed | | | |
| | Item | Cost (€) | Cost (€) |
| **Fixed shading** | 1 | 1250 | € 1,250.00 |

Investment cost, maintenance and repair of the movable shutter system

| Whole Building | | | |
|---|---|---|---|
| Shading | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 100 | € 100.00 |
| **Shading Maintenance** | 1 | 130 | € 50.00 |
| **MVHR Maintenance** | 0 | | € 0.00 |
| **Ventilator Maintenance** | 0 | | € 0.00 |
| **Total** | - | - | **€ 320.00** |

| Wall system repair (every 5 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| Roof repair (every 20 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Roof Maintenance** | 84.05 | 11 | € 924.55 |

| Shading system repair (every 20 years) | | | |
|---|---|---|---|
| | Item | Cost (€) | Cost (€) |
| **Shading Maintenance** | 1 | 400 | € 400.00 |

| Investment cost - Shading system | | | |
|---|---|---|---|
| Case 21: movable | | | |
| | Item | Cost (€) | Cost (€) |
| **Fixed shading** | 1 | 2175 | € 2,175.00 |

Investment cost, maintenance and repair of the MVHR system

| Whole Building | | | |
|---|---|---|---|
| Case 22: MVRH | | | |
| **Component** | Item | Cost (€) | Cost (€) |
| **Wall Maintenance** | 0 | | € 0.00 |
| **Roof Maintenance** | 1 | 40 | € 40.00 |
| **Ground Floor Maintenance** | 1 | 50 | € 50.00 |
| **Windows Glass Maintenance** | 1 | 100 | € 100.00 |
| **Shading Maintenance** | 0 | 0 | € 0.00 |
| **MVHR Maintenance** | 1 | 100 | € 100.00 |
| **Ventilator Maintenance** | 0 | | € 0.00 |
| **Total** | - | - | **€ 290.00** |

| Wall system repair (every 5 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Wall maintenance** | 32.6 | 6 | € 195.60 |

| Roof repair (every 20 years) | | | |
|---|---|---|---|
| | Area ($m^2$) | Cost (€/$m^2$) | Cost (€) |
| **Roof Maintenance** | 84.05 | 11 | € 924.55 |

| MVHR repair (every 20 years) | | | |
|---|---|---|---|
| | Item | Cost (€) | Cost (€) |
| **MVHR repair** | 1 | 2900 | € 2,900.00 |

| Investment cost - MVRH | | | |
|---|---|---|---|
| Case 22 | | | |
| | Item | Cost (€) | Cost (€) |
| **Heat recovery unit** | 1 | 1500 | € 1,500.00 |
| **Diffusers** | 1 | 400 | € 400.00 |

| | | | |
|---|---|---|---|
| **Duct system for filtered air** | 1 | 1000 | € 1,100.00 |
| **Filter material to be exchanged** | 1 | 100 | € 100.00 |
| **Louvers** | 1 | 500 | € 500.00 |
| **$CO_2$ sensor** | 1 | 400 | € 400.00 |
| | | | € 4,000.00 |

**LCCA of the reference building of classroom in the first and ground floor (occupied time: 07:30-13:35)**

| Reference first floor | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | - | | | | | | | | | | | | - |
| **1** | | 3455 | 0.07 | 238 | 194 | 0.17 | 33 | 271 | 0 | 190 | 0 | 1.00 | 461 |
| **2** | | 3455 | 0.07 | 247 | 194 | 0.17 | 34 | 281 | 0 | 190 | 0 | 1.00 | 471 |
| **3** | | 3455 | 0.07 | 257 | 194 | 0.18 | 34 | 291 | 0 | 190 | 0 | 1.00 | 481 |
| **4** | | 3455 | 0.08 | 267 | 194 | 0.18 | 35 | 302 | 0 | 190 | 0 | 1.00 | 492 |
| **5** | | 3455 | 0.08 | 277 | 194 | 0.18 | 36 | 313 | 1120 | 190 | 0 | 1.00 | 1623 |
| **6** | | 3455 | 0.08 | 287 | 194 | 0.19 | 37 | 324 | 0 | 190 | 0 | 1.00 | 514 |
| **7** | | 3455 | 0.09 | 298 | 194 | 0.19 | 37 | 336 | 0 | 190 | 0 | 1.00 | 526 |
| **8** | | 3455 | 0.09 | 310 | 194 | 0.20 | 38 | 348 | 0 | 190 | 0 | 1.00 | 538 |
| **9** | | 3455 | 0.09 | 321 | 194 | 0.20 | 39 | 360 | 0 | 190 | 0 | 1.00 | 550 |
| **10** | | 3455 | 0.10 | 334 | 194 | 0.21 | 40 | 373 | 196 | 190 | 0 | 0.97 | 738 |
| **11** | | 3455 | 0.10 | 346 | 194 | 0.21 | 41 | 387 | 0 | 190 | 0 | 0.97 | 559 |
| **12** | | 3455 | 0.10 | 359 | 194 | 0.21 | 42 | 401 | 0 | 190 | 0 | 0.97 | 572 |
| **13** | | 3455 | 0.11 | 373 | 194 | 0.22 | 43 | 416 | 0 | 190 | 0 | 0.96 | 584 |
| **14** | | 3455 | 0.11 | 387 | 194 | 0.22 | 44 | 431 | 0 | 190 | 0 | 0.96 | 597 |
| **15** | | 3455 | 0.12 | 402 | 194 | 0.23 | 44 | 446 | 196 | 190 | 0 | 0.92 | 766 |
| **16** | | 3455 | 0.12 | 417 | 194 | 0.23 | 45 | 463 | 0 | 190 | 0 | 0.92 | 598 |
| **17** | | 3455 | 0.13 | 433 | 194 | 0.24 | 46 | 479 | 0 | 190 | 0 | 0.91 | 610 |
| **18** | | 3455 | 0.13 | 449 | 194 | 0.24 | 47 | 497 | 0 | 190 | 0 | 0.91 | 622 |
| **19** | | 3455 | 0.14 | 467 | 194 | 0.25 | 49 | 515 | 0 | 190 | 0 | 0.90 | 635 |
| **20** | | 3455 | 0.14 | 484 | 194 | 0.26 | 50 | 534 | 196 | 190 | 0 | 0.85 | 778 |
| **21** | | 3455 | 0.15 | 503 | 194 | 0.26 | 51 | 553 | 0 | 190 | 0 | 0.84 | 623 |
| **22** | | 3455 | 0.15 | 522 | 194 | 0.27 | 52 | 574 | 0 | 190 | 0 | 0.83 | 635 |
| **23** | | 3455 | 0.16 | 542 | 194 | 0.27 | 53 | 595 | 0 | 190 | 0 | 0.82 | 647 |
| **24** | | 3455 | 0.16 | 562 | 194 | 0.28 | 54 | 616 | 0 | 190 | 0 | 0.82 | 659 |
| **25** | | 3455 | 0.17 | 584 | 194 | 0.28 | 55 | 639 | 1120 | 190 | 0 | 0.80 | 1558 |
| **26** | | 3455 | 0.18 | 606 | 194 | 0.29 | 57 | 662 | 0 | 190 | 0 | 0.79 | 675 |
| **27** | | 3455 | 0.18 | 629 | 194 | 0.30 | 58 | 687 | 0 | 190 | 0 | 0.79 | 688 |
| **28** | | 3455 | 0.19 | 653 | 194 | 0.30 | 59 | 712 | 0 | 190 | 0 | 0.78 | 702 |
| **29** | | 3455 | 0.20 | 677 | 194 | 0.31 | 60 | 738 | 0 | 190 | 0 | 0.77 | 715 |
| **30** | | 3455 | 0.20 | 703 | 194 | 0 | 62 | 765 | 0 | 190 | 0 | 0.76 | 730 |
| **Total** | - | 103,663 | 4 | 12,934 | 5,825 | 7 | 1,373 | 14,307 | 2,827 | 5,700 | 0 | 28 | 20,347 |

| Reference ground floor | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh/y) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh/y) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | - | | | | | | | | | | | | - |
| **1** | | 3473 | 0.07 | 240 | 143 | 0.17 | 24 | 264 | 0 | 190 | 0 | 1.00 | 454 |
| **2** | | 3473 | 0.07 | 249 | 143 | 0.17 | 25 | 273 | 0 | 190 | 0 | 1.00 | 463 |
| **3** | | 3473 | 0.07 | 258 | 143 | 0.18 | 25 | 283 | 0 | 190 | 0 | 1.00 | 473 |
| **4** | | 3473 | 0.08 | 268 | 143 | 0.18 | 26 | 294 | 0 | 190 | 0 | 1.00 | 484 |
| **5** | | 3473 | 0.08 | 278 | 143 | 0.18 | 26 | 305 | 1120 | 190 | 0 | 1.00 | 1615 |
| **6** | | 3473 | 0.08 | 289 | 143 | 0.19 | 27 | 316 | 0 | 190 | 0 | 1.00 | 506 |
| **7** | | 3473 | 0.09 | 300 | 143 | 0.19 | 27 | 327 | 0 | 190 | 0 | 1.00 | 517 |
| **8** | | 3473 | 0.09 | 311 | 143 | 0.20 | 28 | 339 | 0 | 190 | 0 | 1.00 | 529 |
| **9** | | 3473 | 0.09 | 323 | 143 | 0.20 | 29 | 352 | 0 | 190 | 0 | 1.00 | 542 |
| **10** | | 3473 | 0.10 | 335 | 143 | 0.21 | 29 | 365 | 196 | 190 | 0 | 0.97 | 729 |
| **11** | | 3473 | 0.10 | 348 | 143 | 0.21 | 30 | 378 | 0 | 190 | 0 | 0.97 | 551 |
| **12** | | 3473 | 0.10 | 361 | 143 | 0.21 | 31 | 392 | 0 | 190 | 0 | 0.97 | 563 |
| **13** | | 3473 | 0.11 | 375 | 143 | 0.22 | 31 | 406 | 0 | 190 | 0 | 0.96 | 575 |
| **14** | | 3473 | 0.11 | 389 | 143 | 0.22 | 32 | 421 | 0 | 190 | 0 | 0.96 | 588 |
| **15** | | 3473 | 0.12 | 404 | 143 | 0.23 | 33 | 437 | 196 | 190 | 0 | 0.92 | 757 |
| **16** | | 3473 | 0.12 | 419 | 143 | 0.23 | 33 | 453 | 0 | 190 | 0 | 0.92 | 589 |
| **17** | | 3473 | 0.13 | 435 | 143 | 0.24 | 34 | 469 | 0 | 190 | 0 | 0.91 | 601 |
| **18** | | 3473 | 0.13 | 452 | 143 | 0.24 | 35 | 487 | 0 | 190 | 0 | 0.91 | 613 |
| **19** | | 3473 | 0.14 | 469 | 143 | 0.25 | 36 | 505 | 0 | 190 | 0 | 0.90 | 626 |
| **20** | | 3473 | 0.14 | 487 | 143 | 0.26 | 36 | 523 | 196 | 190 | 0 | 0.85 | 769 |
| **21** | | 3473 | 0.15 | 505 | 143 | 0.26 | 37 | 543 | 0 | 190 | 0 | 0.84 | 614 |
| **22** | | 3473 | 0.15 | 525 | 143 | 0.27 | 38 | 563 | 0 | 190 | 0 | 0.83 | 626 |
| **23** | | 3473 | 0.16 | 544 | 143 | 0.27 | 39 | 583 | 0 | 190 | 0 | 0.82 | 638 |
| **24** | | 3473 | 0.16 | 565 | 143 | 0.28 | 40 | 605 | 0 | 190 | 0 | 0.82 | 650 |
| **25** | | 3473 | 0.17 | 587 | 143 | 0.28 | 41 | 627 | 1120 | 190 | 0 | 0.80 | 1549 |
| **26** | | 3473 | 0.18 | 609 | 143 | 0.29 | 41 | 650 | 0 | 190 | 0 | 0.79 | 666 |
| **27** | | 3473 | 0.18 | 632 | 143 | 0.30 | 42 | 674 | 0 | 190 | 0 | 0.79 | 679 |
| **28** | | 3473 | 0.19 | 656 | 143 | 0.30 | 43 | 699 | 0 | 190 | 0 | 0.78 | 692 |
| **29** | | 3473 | 0.20 | 681 | 143 | 0.31 | 44 | 725 | 0 | 190 | 0 | 0.77 | 706 |
| **30** | | 3473 | 0.20 | 707 | 143 | 0.32 | 45 | 752 | 0 | 190 | 0 | 0.76 | 720 |
| **Total** | - | 104,204 | 4 | 13,001 | 4,277 | 7 | 1,008 | 14,010 | 2,827 | 5,700 | - | 27 | 20,081 |

**LCCA of retrofit scenarios of classroom in the first and ground floor (occupied time: 07:30-13:35)**

| Case 1 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 1,391 | | | | | | | | | | | | 1,391 |
| **1** | | 3264 | 0.07 | 225 | 139 | 0.17 | 24 | 249 | 0 | 190 | 0 | 1.00 | 439 |
| **2** | | 3264 | 0.07 | 234 | 139 | 0.17 | 24 | 258 | 0 | 190 | 0 | 1.00 | 448 |
| **3** | | 3264 | 0.07 | 243 | 139 | 0.18 | 25 | 267 | 0 | 190 | 0 | 1.00 | 457 |
| **4** | | 3264 | 0.08 | 252 | 139 | 0.18 | 25 | 277 | 0 | 190 | 0 | 1.00 | 467 |
| **5** | | 3264 | 0.08 | 261 | 139 | 0.18 | 26 | 287 | 925 | 190 | 0 | 1.00 | 1402 |
| **6** | | 3264 | 0.08 | 271 | 139 | 0.19 | 26 | 298 | 0 | 190 | 0 | 1.00 | 488 |
| **7** | | 3264 | 0.09 | 282 | 139 | 0.19 | 27 | 309 | 0 | 190 | 0 | 1.00 | 499 |
| **8** | | 3264 | 0.09 | 292 | 139 | 0.20 | 27 | 320 | 0 | 190 | 0 | 1.00 | 510 |
| **9** | | 3264 | 0.09 | 304 | 139 | 0.20 | 28 | 332 | 0 | 190 | 0 | 1.00 | 522 |
| **10** | | 3264 | 0.10 | 315 | 139 | 0.21 | 29 | 344 | 0 | 190 | 0 | 0.97 | 519 |
| **11** | | 3264 | 0.10 | 327 | 139 | 0.21 | 29 | 356 | 0 | 190 | 0 | 0.97 | 530 |
| **12** | | 3264 | 0.10 | 339 | 139 | 0.21 | 30 | 369 | 0 | 190 | 0 | 0.97 | 541 |
| **13** | | 3264 | 0.11 | 352 | 139 | 0.22 | 31 | 383 | 0 | 190 | 0 | 0.96 | 552 |
| **14** | | 3264 | 0.11 | 366 | 139 | 0.22 | 31 | 397 | 0 | 190 | 0 | 0.96 | 564 |
| **15** | | 3264 | 0.12 | 380 | 139 | 0.23 | 32 | 412 | 196 | 190 | 0 | 0.92 | 734 |
| **16** | | 3264 | 0.12 | 394 | 139 | 0.23 | 33 | 427 | 0 | 190 | 0 | 0.92 | 565 |
| **17** | | 3264 | 0.13 | 409 | 139 | 0.24 | 33 | 442 | 0 | 190 | 0 | 0.91 | 576 |
| **18** | | 3264 | 0.13 | 425 | 139 | 0.24 | 34 | 459 | 0 | 190 | 0 | 0.91 | 588 |
| **19** | | 3264 | 0.14 | 441 | 139 | 0.25 | 35 | 476 | 0 | 190 | 0 | 0.90 | 600 |
| **20** | | 3264 | 0.14 | 458 | 139 | 0.26 | 36 | 493 | 0 | 190 | 0 | 0.85 | 578 |
| **21** | | 3264 | 0.15 | 475 | 139 | 0.26 | 36 | 511 | 0 | 190 | 0 | 0.84 | 588 |
| **22** | | 3264 | 0.15 | 493 | 139 | 0.27 | 37 | 530 | 0 | 190 | 0 | 0.83 | 599 |
| **23** | | 3264 | 0.16 | 512 | 139 | 0.27 | 38 | 550 | 0 | 190 | 0 | 0.82 | 610 |
| **24** | | 3264 | 0.16 | 531 | 139 | 0.28 | 39 | 570 | 0 | 190 | 0 | 0.82 | 621 |
| **25** | | 3264 | 0.17 | 551 | 139 | 0.28 | 40 | 591 | 925 | 190 | 0 | 0.80 | 1363 |
| **26** | | 3264 | 0.18 | 572 | 139 | 0.29 | 41 | 613 | 0 | 190 | 0 | 0.79 | 636 |
| **27** | | 3264 | 0.18 | 594 | 139 | 0.30 | 41 | 635 | 0 | 190 | 0 | 0.79 | 648 |
| **28** | | 3264 | 0.19 | 617 | 139 | 0.30 | 42 | 659 | 0 | 190 | 0 | 0.78 | 661 |
| **29** | | 3264 | 0.20 | 640 | 139 | 0.31 | 43 | 683 | 0 | 190 | 0 | 0.77 | 673 |
| **30** | | 3264 | 0.20 | 664 | 139 | 0.32 | 44 | 709 | 0 | 190 | 0 | 0.76 | 687 |
| **Total** | 1,391 | 97,930 | 4 | 12,219 | 4,176 | 7 | 984 | 13,203 | 2,045 | 5,700 | - | 27 | 20,053 |

| Case 2 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 1,521 | | | | | | | | | | | | 1,521 |
| **1** | | 3241 | 0.07 | 224 | 140 | 0.17 | 24 | 247 | 0 | 190 | 0 | 1.00 | 437 |
| **2** | | 3241 | 0.07 | 232 | 140 | 0.17 | 24 | 256 | 0 | 190 | 0 | 1.00 | 446 |
| **3** | | 3241 | 0.07 | 241 | 140 | 0.18 | 25 | 266 | 0 | 190 | 0 | 1.00 | 456 |
| **4** | | 3241 | 0.08 | 250 | 140 | 0.18 | 25 | 275 | 0 | 190 | 0 | 1.00 | 465 |
| **5** | | 3241 | 0.08 | 260 | 140 | 0.18 | 26 | 285 | 925 | 190 | 0 | 1.00 | 1400 |
| **6** | | 3241 | 0.08 | 269 | 140 | 0.19 | 26 | 296 | 0 | 190 | 0 | 1.00 | 486 |
| **7** | | 3241 | 0.09 | 280 | 140 | 0.19 | 27 | 307 | 0 | 190 | 0 | 1.00 | 497 |
| **8** | | 3241 | 0.09 | 290 | 140 | 0.20 | 27 | 318 | 0 | 190 | 0 | 1.00 | 508 |
| **9** | | 3241 | 0.09 | 301 | 140 | 0.20 | 28 | 329 | 0 | 190 | 0 | 1.00 | 519 |
| **10** | | 3241 | 0.10 | 313 | 140 | 0.21 | 29 | 342 | 0 | 190 | 0 | 0.97 | 517 |
| **11** | | 3241 | 0.10 | 325 | 140 | 0.21 | 29 | 354 | 0 | 190 | 0 | 0.97 | 528 |
| **12** | | 3241 | 0.10 | 337 | 140 | 0.21 | 30 | 367 | 0 | 190 | 0 | 0.97 | 539 |
| **13** | | 3241 | 0.11 | 350 | 140 | 0.22 | 31 | 381 | 0 | 190 | 0 | 0.96 | 550 |
| **14** | | 3241 | 0.11 | 363 | 140 | 0.22 | 31 | 395 | 0 | 190 | 0 | 0.96 | 562 |
| **15** | | 3241 | 0.12 | 377 | 140 | 0.23 | 32 | 409 | 196 | 190 | 0 | 0.92 | 732 |
| **16** | | 3241 | 0.12 | 391 | 140 | 0.23 | 33 | 424 | 0 | 190 | 0 | 0.92 | 562 |
| **17** | | 3241 | 0.13 | 406 | 140 | 0.24 | 33 | 440 | 0 | 190 | 0 | 0.91 | 574 |
| **18** | | 3241 | 0.13 | 422 | 140 | 0.24 | 34 | 456 | 0 | 190 | 0 | 0.91 | 585 |
| **19** | | 3241 | 0.14 | 438 | 140 | 0.25 | 35 | 473 | 0 | 190 | 0 | 0.90 | 597 |
| **20** | | 3241 | 0.14 | 454 | 140 | 0.26 | 36 | 490 | 0 | 190 | 0 | 0.85 | 575 |
| **21** | | 3241 | 0.15 | 472 | 140 | 0.26 | 36 | 508 | 0 | 190 | 0 | 0.84 | 585 |
| **22** | | 3241 | 0.15 | 489 | 140 | 0.27 | 37 | 527 | 0 | 190 | 0 | 0.83 | 596 |
| **23** | | 3241 | 0.16 | 508 | 140 | 0.27 | 38 | 546 | 0 | 190 | 0 | 0.82 | 607 |
| **24** | | 3241 | 0.16 | 527 | 140 | 0.28 | 39 | 566 | 0 | 190 | 0 | 0.82 | 618 |
| **25** | | 3241 | 0.17 | 547 | 140 | 0.28 | 40 | 587 | 925 | 190 | 0 | 0.80 | 1360 |
| **26** | | 3241 | 0.18 | 568 | 140 | 0.29 | 41 | 609 | 0 | 190 | 0 | 0.79 | 633 |
| **27** | | 3241 | 0.18 | 590 | 140 | 0.30 | 42 | 631 | 0 | 190 | 0 | 0.79 | 645 |
| **28** | | 3241 | 0.19 | 612 | 140 | 0.30 | 42 | 655 | 0 | 190 | 0 | 0.78 | 657 |
| **29** | | 3241 | 0.20 | 635 | 140 | 0.31 | 43 | 679 | 0 | 190 | 0 | 0.77 | 670 |
| **30** | | 3241 | 0.20 | 660 | 140 | 0.32 | 44 | 704 | 0 | 190 | 0 | 0.76 | 683 |
| **Total** | 1,521 | 97,236 | 4 | 12,132 | 4,193 | 7 | 988 | 13,120 | 2,045 | 5,700 | - | 28 | 20,111 |

**Case 3**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,619 | | | | | | | | | | | | 1,619 |
| **1** | | 3232 | 0.07 | 223 | 140 | 0.17 | 24 | 247 | 0 | 190 | 0 | 1.00 | 437 |
| **2** | | 3232 | 0.07 | 231 | 140 | 0.17 | 24 | 256 | 0 | 190 | 0 | 1.00 | 446 |
| **3** | | 3232 | 0.07 | 240 | 140 | 0.18 | 25 | 265 | 0 | 190 | 0 | 1.00 | 455 |
| **4** | | 3232 | 0.08 | 249 | 140 | 0.18 | 25 | 275 | 0 | 190 | 0 | 1.00 | 465 |
| **5** | | 3232 | 0.08 | 259 | 140 | 0.18 | 26 | 285 | 925 | 190 | 0 | 1.00 | 1399 |
| **6** | | 3232 | 0.08 | 269 | 140 | 0.19 | 26 | 295 | 0 | 190 | 0 | 1.00 | 485 |
| **7** | | 3232 | 0.09 | 279 | 140 | 0.19 | 27 | 306 | 0 | 190 | 0 | 1.00 | 496 |
| **8** | | 3232 | 0.09 | 290 | 140 | 0.20 | 28 | 317 | 0 | 190 | 0 | 1.00 | 507 |
| **9** | | 3232 | 0.09 | 301 | 140 | 0.20 | 28 | 329 | 0 | 190 | 0 | 1.00 | 519 |
| **10** | | 3232 | 0.10 | 312 | 140 | 0.21 | 29 | 341 | 0 | 190 | 0 | 0.97 | 516 |
| **11** | | 3232 | 0.10 | 324 | 140 | 0.21 | 29 | 353 | 0 | 190 | 0 | 0.97 | 527 |
| **12** | | 3232 | 0.10 | 336 | 140 | 0.21 | 30 | 366 | 0 | 190 | 0 | 0.97 | 538 |
| **13** | | 3232 | 0.11 | 349 | 140 | 0.22 | 31 | 380 | 0 | 190 | 0 | 0.96 | 549 |
| **14** | | 3232 | 0.11 | 362 | 140 | 0.22 | 31 | 394 | 0 | 190 | 0 | 0.96 | 561 |
| **15** | | 3232 | 0.12 | 376 | 140 | 0.23 | 32 | 408 | 196 | 190 | 0 | 0.92 | 731 |
| **16** | | 3232 | 0.12 | 390 | 140 | 0.23 | 33 | 423 | 0 | 190 | 0 | 0.92 | 561 |
| **17** | | 3232 | 0.13 | 405 | 140 | 0.24 | 34 | 439 | 0 | 190 | 0 | 0.91 | 573 |
| **18** | | 3232 | 0.13 | 420 | 140 | 0.24 | 34 | 455 | 0 | 190 | 0 | 0.91 | 584 |
| **19** | | 3232 | 0.14 | 436 | 140 | 0.25 | 35 | 471 | 0 | 190 | 0 | 0.90 | 596 |
| **20** | | 3232 | 0.14 | 453 | 140 | 0.26 | 36 | 489 | 0 | 190 | 0 | 0.85 | 574 |
| **21** | | 3232 | 0.15 | 470 | 140 | 0.26 | 37 | 507 | 0 | 190 | 0 | 0.84 | 584 |
| **22** | | 3232 | 0.15 | 488 | 140 | 0.27 | 37 | 525 | 0 | 190 | 0 | 0.83 | 595 |
| **23** | | 3232 | 0.16 | 507 | 140 | 0.27 | 38 | 545 | 0 | 190 | 0 | 0.82 | 606 |
| **24** | | 3232 | 0.16 | 526 | 140 | 0.28 | 39 | 565 | 0 | 190 | 0 | 0.82 | 617 |
| **25** | | 3232 | 0.17 | 546 | 140 | 0.28 | 40 | 586 | 925 | 190 | 0 | 0.80 | 1359 |
| **26** | | 3232 | 0.18 | 567 | 140 | 0.29 | 41 | 607 | 0 | 190 | 0 | 0.79 | 632 |
| **27** | | 3232 | 0.18 | 588 | 140 | 0.30 | 42 | 630 | 0 | 190 | 0 | 0.79 | 644 |
| **28** | | 3232 | 0.19 | 610 | 140 | 0.30 | 43 | 653 | 0 | 190 | 0 | 0.78 | 656 |
| **29** | | 3232 | 0.20 | 634 | 140 | 0.31 | 44 | 677 | 0 | 190 | 0 | 0.77 | 669 |
| **30** | | 3232 | 0.20 | 658 | 140 | 0.32 | 44 | 702 | 0 | 190 | 0 | 0.76 | 682 |
| **Total** | 1,619 | 96,962 | 4 | 12,098 | 4,201 | 7 | 990 | 13,088 | 2,045 | 5,700 | - | 28 | 20,180 |

**Case 4**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,782 | | | | | | | | | | | | 1,782 |
| **1** | | 3218 | 0.07 | 222 | 140 | 0.17 | 24 | 246 | 0 | 190 | 0 | 1.00 | 436 |
| **2** | | 3218 | 0.07 | 230 | 140 | 0.17 | 24 | 255 | 0 | 190 | 0 | 1.00 | 445 |
| **3** | | 3218 | 0.07 | 239 | 140 | 0.18 | 25 | 264 | 0 | 190 | 0 | 1.00 | 454 |
| **4** | | 3218 | 0.08 | 248 | 140 | 0.18 | 25 | 274 | 0 | 190 | 0 | 1.00 | 464 |
| **5** | | 3218 | 0.08 | 258 | 140 | 0.18 | 26 | 284 | 925 | 190 | 0 | 1.00 | 1398 |
| **6** | | 3218 | 0.08 | 268 | 140 | 0.19 | 26 | 294 | 0 | 190 | 0 | 1.00 | 484 |
| **7** | | 3218 | 0.09 | 278 | 140 | 0.19 | 27 | 305 | 0 | 190 | 0 | 1.00 | 495 |
| **8** | | 3218 | 0.09 | 288 | 140 | 0.20 | 28 | 316 | 0 | 190 | 0 | 1.00 | 506 |
| **9** | | 3218 | 0.09 | 299 | 140 | 0.20 | 28 | 327 | 0 | 190 | 0 | 1.00 | 517 |
| **10** | | 3218 | 0.10 | 311 | 140 | 0.21 | 29 | 339 | 0 | 190 | 0 | 0.97 | 515 |
| **11** | | 3218 | 0.10 | 322 | 140 | 0.21 | 29 | 352 | 0 | 190 | 0 | 0.97 | 525 |
| **12** | | 3218 | 0.10 | 335 | 140 | 0.21 | 30 | 365 | 0 | 190 | 0 | 0.97 | 537 |
| **13** | | 3218 | 0.11 | 347 | 140 | 0.22 | 31 | 378 | 0 | 190 | 0 | 0.96 | 548 |
| **14** | | 3218 | 0.11 | 361 | 140 | 0.22 | 31 | 392 | 0 | 190 | 0 | 0.96 | 560 |
| **15** | | 3218 | 0.12 | 374 | 140 | 0.23 | 32 | 406 | 196 | 190 | 0 | 0.92 | 730 |
| **16** | | 3218 | 0.12 | 389 | 140 | 0.23 | 33 | 421 | 0 | 190 | 0 | 0.92 | 560 |
| **17** | | 3218 | 0.13 | 403 | 140 | 0.24 | 34 | 437 | 0 | 190 | 0 | 0.91 | 571 |
| **18** | | 3218 | 0.13 | 419 | 140 | 0.24 | 34 | 453 | 0 | 190 | 0 | 0.91 | 583 |
| **19** | | 3218 | 0.14 | 435 | 140 | 0.25 | 35 | 470 | 0 | 190 | 0 | 0.90 | 594 |
| **20** | | 3218 | 0.14 | 451 | 140 | 0.26 | 36 | 487 | 0 | 190 | 0 | 0.85 | 572 |
| **21** | | 3218 | 0.15 | 468 | 140 | 0.26 | 37 | 505 | 0 | 190 | 0 | 0.84 | 583 |
| **22** | | 3218 | 0.15 | 486 | 140 | 0.27 | 37 | 523 | 0 | 190 | 0 | 0.83 | 593 |
| **23** | | 3218 | 0.16 | 504 | 140 | 0.27 | 38 | 543 | 0 | 190 | 0 | 0.82 | 604 |
| **24** | | 3218 | 0.16 | 524 | 140 | 0.28 | 39 | 563 | 0 | 190 | 0 | 0.82 | 616 |
| **25** | | 3218 | 0.17 | 544 | 140 | 0.28 | 40 | 583 | 925 | 190 | 0 | 0.80 | 1357 |
| **26** | | 3218 | 0.18 | 564 | 140 | 0.29 | 41 | 605 | 0 | 190 | 0 | 0.79 | 630 |
| **27** | | 3218 | 0.18 | 586 | 140 | 0.30 | 42 | 627 | 0 | 190 | 0 | 0.79 | 642 |
| **28** | | 3218 | 0.19 | 608 | 140 | 0.30 | 43 | 651 | 0 | 190 | 0 | 0.78 | 654 |
| **29** | | 3218 | 0.20 | 631 | 140 | 0.31 | 44 | 675 | 0 | 190 | 0 | 0.77 | 667 |
| **30** | | 3218 | 0.20 | 655 | 140 | 0.32 | 45 | 699 | 0 | 190 | 0 | 0.76 | 680 |
| **Total** | 1,782 | 96,548 | 4 | 12,046 | 4,211 | 7 | 993 | 13,039 | 2,045 | 5,700 | - | 27 | 20,300 |

**Case 5**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,024 | | | | | | | | | | | | 3,024 |
| **1** | | 3042 | 0.07 | 210 | 95 | 0.17 | 16 | 226 | 0 | 190 | 0 | 1.00 | 416 |
| **2** | | 3042 | 0.07 | 218 | 95 | 0.17 | 16 | 234 | 0 | 190 | 0 | 1.00 | 424 |
| **3** | | 3042 | 0.07 | 226 | 95 | 0.18 | 17 | 243 | 0 | 190 | 0 | 1.00 | 433 |
| **4** | | 3042 | 0.08 | 235 | 95 | 0.18 | 17 | 252 | 0 | 190 | 0 | 1.00 | 442 |
| **5** | | 3042 | 0.08 | 244 | 95 | 0.18 | 17 | 261 | 196 | 190 | 0 | 1.00 | 647 |
| **6** | | 3042 | 0.08 | 253 | 95 | 0.19 | 18 | 271 | 0 | 190 | 0 | 1.00 | 461 |
| **7** | | 3042 | 0.09 | 263 | 95 | 0.19 | 18 | 281 | 0 | 190 | 0 | 1.00 | 471 |
| **8** | | 3042 | 0.09 | 272 | 95 | 0.20 | 19 | 291 | 0 | 190 | 0 | 1.00 | 481 |
| **9** | | 3042 | 0.09 | 283 | 95 | 0.20 | 19 | 302 | 0 | 190 | 0 | 1.00 | 492 |
| **10** | | 3042 | 0.10 | 294 | 95 | 0.21 | 19 | 313 | 196 | 190 | 0 | 0.97 | 679 |
| **11** | | 3042 | 0.10 | 305 | 95 | 0.21 | 20 | 325 | 0 | 190 | 0 | 0.97 | 499 |
| **12** | | 3042 | 0.10 | 316 | 95 | 0.21 | 20 | 337 | 0 | 190 | 0 | 0.97 | 509 |
| **13** | | 3042 | 0.11 | 328 | 95 | 0.22 | 21 | 349 | 0 | 190 | 0 | 0.96 | 520 |
| **14** | | 3042 | 0.11 | 341 | 95 | 0.22 | 21 | 362 | 0 | 190 | 0 | 0.96 | 531 |
| **15** | | 3042 | 0.12 | 354 | 95 | 0.23 | 22 | 375 | 196 | 190 | 0 | 0.92 | 701 |
| **16** | | 3042 | 0.12 | 367 | 95 | 0.23 | 22 | 389 | 0 | 190 | 0 | 0.92 | 531 |
| **17** | | 3042 | 0.13 | 381 | 95 | 0.24 | 23 | 404 | 0 | 190 | 0 | 0.91 | 541 |
| **18** | | 3042 | 0.13 | 396 | 95 | 0.24 | 23 | 419 | 0 | 190 | 0 | 0.91 | 552 |
| **19** | | 3042 | 0.14 | 411 | 95 | 0.25 | 24 | 434 | 0 | 190 | 0 | 0.90 | 563 |
| **20** | | 3042 | 0.14 | 426 | 95 | 0.26 | 24 | 451 | 196 | 190 | 0 | 0.85 | 707 |
| **21** | | 3042 | 0.15 | 442 | 95 | 0.26 | 25 | 467 | 0 | 190 | 0 | 0.84 | 551 |
| **22** | | 3042 | 0.15 | 459 | 95 | 0.27 | 25 | 485 | 0 | 190 | 0 | 0.83 | 561 |
| **23** | | 3042 | 0.16 | 477 | 95 | 0.27 | 26 | 503 | 0 | 190 | 0 | 0.82 | 571 |
| **24** | | 3042 | 0.16 | 495 | 95 | 0.28 | 26 | 521 | 0 | 190 | 0 | 0.82 | 582 |
| **25** | | 3042 | 0.17 | 514 | 95 | 0.28 | 27 | 541 | 196 | 190 | 0 | 0.80 | 740 |
| **26** | | 3042 | 0.18 | 533 | 95 | 0.29 | 28 | 561 | 0 | 190 | 0 | 0.79 | 595 |
| **27** | | 3042 | 0.18 | 553 | 95 | 0.30 | 28 | 582 | 0 | 190 | 0 | 0.79 | 606 |
| **28** | | 3042 | 0.19 | 574 | 95 | 0.30 | 29 | 603 | 0 | 190 | 0 | 0.78 | 617 |
| **29** | | 3042 | 0.20 | 596 | 95 | 0.31 | 29 | 626 | 0 | 190 | 0 | 0.77 | 629 |
| **30** | | 3042 | 0.20 | 619 | 95 | 0.32 | 30 | 649 | 0 | 190 | 150 | 0.76 | 527 |
| | | | | | | | | | | | | | 0.00 |
| **Total** | 3,024 | 91,249 | 4 | 11,385 | 2,844 | 7 | 670 | 12,055 | 978 | 5,700 | 150 | 27 | 19,601 |

**Case 6**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,444 | | | | | | | | | | | | 3,444 |
| **1** | | 2991 | 0.07 | 206 | 90 | 0.17 | 15 | 222 | 0 | 190 | 0 | 1.00 | 396 |
| **2** | | 2991 | 0.07 | 214 | 90 | 0.17 | 15 | 230 | 0 | 190 | 0 | 1.00 | 420 |
| **3** | | 2991 | 0.07 | 222 | 90 | 0.18 | 16 | 238 | 0 | 190 | 0 | 1.00 | 428 |
| **4** | | 2991 | 0.08 | 231 | 90 | 0.18 | 16 | 247 | 0 | 190 | 0 | 1.00 | 437 |
| **5** | | 2991 | 0.08 | 240 | 90 | 0.18 | 17 | 256 | 196 | 190 | 0 | 1.00 | 642 |
| **6** | | 2991 | 0.08 | 249 | 90 | 0.19 | 17 | 266 | 0 | 190 | 0 | 1.00 | 456 |
| **7** | | 2991 | 0.09 | 258 | 90 | 0.19 | 17 | 275 | 0 | 190 | 0 | 1.00 | 465 |
| **8** | | 2991 | 0.09 | 268 | 90 | 0.20 | 18 | 286 | 0 | 190 | 0 | 1.00 | 476 |
| **9** | | 2991 | 0.09 | 278 | 90 | 0.20 | 18 | 296 | 0 | 190 | 0 | 1.00 | 486 |
| **10** | | 2991 | 0.10 | 289 | 90 | 0.21 | 18 | 307 | 196 | 190 | 0 | 0.97 | 674 |
| **11** | | 2991 | 0.10 | 300 | 90 | 0.21 | 19 | 319 | 0 | 190 | 0 | 0.97 | 493 |
| **12** | | 2991 | 0.10 | 311 | 90 | 0.21 | 19 | 330 | 0 | 190 | 0 | 0.97 | 503 |
| **13** | | 2991 | 0.11 | 323 | 90 | 0.22 | 20 | 343 | 0 | 190 | 0 | 0.96 | 514 |
| **14** | | 2991 | 0.11 | 335 | 90 | 0.22 | 20 | 355 | 0 | 190 | 0 | 0.96 | 524 |
| **15** | | 2991 | 0.12 | 348 | 90 | 0.23 | 21 | 368 | 196 | 190 | 0 | 0.92 | 694 |
| **16** | | 2991 | 0.12 | 361 | 90 | 0.23 | 21 | 382 | 0 | 190 | 0 | 0.92 | 524 |
| **17** | | 2991 | 0.13 | 375 | 90 | 0.24 | 21 | 396 | 0 | 190 | 0 | 0.91 | 534 |
| **18** | | 2991 | 0.13 | 389 | 90 | 0.24 | 22 | 411 | 0 | 190 | 0 | 0.91 | 544 |
| **19** | | 2991 | 0.14 | 404 | 90 | 0.25 | 22 | 426 | 0 | 190 | 0 | 0.90 | 555 |
| **20** | | 2991 | 0.14 | 419 | 90 | 0.26 | 23 | 442 | 196 | 190 | 0 | 0.85 | 700 |
| **21** | | 2991 | 0.15 | 435 | 90 | 0.26 | 23 | 459 | 0 | 190 | 0 | 0.84 | 544 |
| **22** | | 2991 | 0.15 | 452 | 90 | 0.27 | 24 | 476 | 0 | 190 | 0 | 0.83 | 553 |
| **23** | | 2991 | 0.16 | 469 | 90 | 0.27 | 24 | 493 | 0 | 190 | 0 | 0.82 | 563 |
| **24** | | 2991 | 0.16 | 487 | 90 | 0.28 | 25 | 512 | 0 | 190 | 0 | 0.82 | 574 |
| **25** | | 2991 | 0.17 | 505 | 90 | 0.28 | 26 | 531 | 196 | 190 | 0 | 0.80 | 732 |
| **26** | | 2991 | 0.18 | 524 | 90 | 0.29 | 26 | 550 | 0 | 190 | 0 | 0.79 | 587 |
| **27** | | 2991 | 0.18 | 544 | 90 | 0.30 | 27 | 571 | 0 | 190 | 0 | 0.79 | 597 |
| **28** | | 2991 | 0.19 | 565 | 90 | 0.30 | 27 | 592 | 0 | 190 | 0 | 0.78 | 609 |
| **29** | | 2991 | 0.20 | 586 | 90 | 0.31 | 28 | 614 | 0 | 190 | 0 | 0.77 | 620 |
| **30** | | 2991 | 0.20 | 609 | 90 | 0.32 | 28 | 637 | 0 | 190 | 150 | 0.76 | 518 |
| **Total** | 3,444 | 89,736 | 4 | 11,196 | 2,688 | 7 | 634 | 11,830 | 978 | 5,700 | 150 | 27 | 19,807 |

**Case 7**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,864 | | | | | | | | | | | | 3,864 |
| **1** | | 2971 | 0.07 | 205 | 88 | 0.17 | 15 | 220 | 0 | 190 | 0 | 1.00 | 395 |
| **2** | | 2971 | 0.07 | 213 | 88 | 0.17 | 15 | 228 | 0 | 190 | 0 | 1.00 | 418 |
| **3** | | 2971 | 0.07 | 221 | 88 | 0.18 | 15 | 236 | 0 | 190 | 0 | 1.00 | 426 |
| **4** | | 2971 | 0.08 | 229 | 88 | 0.18 | 16 | 245 | 0 | 190 | 0 | 1.00 | 435 |
| **5** | | 2971 | 0.08 | 238 | 88 | 0.18 | 16 | 254 | 196 | 190 | 0 | 1.00 | 640 |
| **6** | | 2971 | 0.08 | 247 | 88 | 0.19 | 17 | 263 | 0 | 190 | 0 | 1.00 | 453 |
| **7** | | 2971 | 0.09 | 256 | 88 | 0.19 | 17 | 273 | 0 | 190 | 0 | 1.00 | 463 |
| **8** | | 2971 | 0.09 | 266 | 88 | 0.20 | 17 | 283 | 0 | 190 | 0 | 1.00 | 473 |
| **9** | | 2971 | 0.09 | 276 | 88 | 0.20 | 18 | 294 | 0 | 190 | 0 | 1.00 | 484 |
| **10** | | 2971 | 0.10 | 287 | 88 | 0.21 | 18 | 305 | 196 | 190 | 0 | 0.97 | 671 |
| **11** | | 2971 | 0.10 | 298 | 88 | 0.21 | 18 | 316 | 0 | 190 | 0 | 0.97 | 491 |
| **12** | | 2971 | 0.10 | 309 | 88 | 0.21 | 19 | 328 | 0 | 190 | 0 | 0.97 | 501 |
| **13** | | 2971 | 0.11 | 321 | 88 | 0.22 | 19 | 340 | 0 | 190 | 0 | 0.96 | 511 |
| **14** | | 2971 | 0.11 | 333 | 88 | 0.22 | 20 | 353 | 0 | 190 | 0 | 0.96 | 522 |
| **15** | | 2971 | 0.12 | 346 | 88 | 0.23 | 20 | 366 | 196 | 190 | 0 | 0.92 | 692 |
| **16** | | 2971 | 0.12 | 359 | 88 | 0.23 | 21 | 379 | 0 | 190 | 0 | 0.92 | 521 |
| **17** | | 2971 | 0.13 | 372 | 88 | 0.24 | 21 | 393 | 0 | 190 | 0 | 0.91 | 531 |
| **18** | | 2971 | 0.13 | 386 | 88 | 0.24 | 21 | 408 | 0 | 190 | 0 | 0.91 | 542 |
| **19** | | 2971 | 0.14 | 401 | 88 | 0.25 | 22 | 423 | 0 | 190 | 0 | 0.90 | 552 |
| **20** | | 2971 | 0.14 | 416 | 88 | 0.26 | 22 | 439 | 196 | 190 | 0 | 0.85 | 697 |
| **21** | | 2971 | 0.15 | 432 | 88 | 0.26 | 23 | 455 | 0 | 190 | 0 | 0.84 | 541 |
| **22** | | 2971 | 0.15 | 449 | 88 | 0.27 | 23 | 472 | 0 | 190 | 0 | 0.83 | 550 |
| **23** | | 2971 | 0.16 | 466 | 88 | 0.27 | 24 | 490 | 0 | 190 | 0 | 0.82 | 560 |
| **24** | | 2971 | 0.16 | 483 | 88 | 0.28 | 24 | 508 | 0 | 190 | 0 | 0.82 | 571 |
| **25** | | 2971 | 0.17 | 502 | 88 | 0.28 | 25 | 527 | 196 | 190 | 0 | 0.80 | 729 |
| **26** | | 2971 | 0.18 | 521 | 88 | 0.29 | 26 | 546 | 0 | 190 | 0 | 0.79 | 583 |
| **27** | | 2971 | 0.18 | 541 | 88 | 0.30 | 26 | 567 | 0 | 190 | 0 | 0.79 | 594 |
| **28** | | 2971 | 0.19 | 561 | 88 | 0.30 | 27 | 588 | 0 | 190 | 0 | 0.78 | 605 |
| **29** | | 2971 | 0.20 | 582 | 88 | 0.31 | 27 | 610 | 0 | 190 | 0 | 0.77 | 617 |
| **30** | | 2971 | 0.20 | 605 | 88 | 0.32 | 28 | 632 | 0 | 190 | 150 | 0.76 | 514 |
| **Total** | 3,864 | 89,120 | 4 | 11,119 | 2,629 | 7 | 620 | 11,739 | 978 | 5,700 | 150 | 27 | 20,147 |

**Case 8**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,284 | | | | | | | | | | | | 4,284 |
| **1** | | 2959 | 0.07 | 204 | 87 | 0.17 | 15 | 219 | 0 | 190 | 0 | 1.00 | 394 |
| **2** | | 2959 | 0.07 | 212 | 87 | 0.17 | 15 | 227 | 0 | 190 | 0 | 1.00 | 417 |
| **3** | | 2959 | 0.07 | 220 | 87 | 0.18 | 15 | 235 | 0 | 190 | 0 | 1.00 | 425 |
| **4** | | 2959 | 0.08 | 228 | 87 | 0.18 | 16 | 244 | 0 | 190 | 0 | 1.00 | 434 |
| **5** | | 2959 | 0.08 | 237 | 87 | 0.18 | 16 | 253 | 196 | 190 | 0 | 1.00 | 639 |
| **6** | | 2959 | 0.08 | 246 | 87 | 0.19 | 16 | 262 | 0 | 190 | 0 | 1.00 | 452 |
| **7** | | 2959 | 0.09 | 255 | 87 | 0.19 | 17 | 272 | 0 | 190 | 0 | 1.00 | 462 |
| **8** | | 2959 | 0.09 | 265 | 87 | 0.20 | 17 | 282 | 0 | 190 | 0 | 1.00 | 472 |
| **9** | | 2959 | 0.09 | 275 | 87 | 0.20 | 17 | 293 | 0 | 190 | 0 | 1.00 | 483 |
| **10** | | 2959 | 0.10 | 286 | 87 | 0.21 | 18 | 303 | 196 | 190 | 0 | 0.97 | 670 |
| **11** | | 2959 | 0.10 | 296 | 87 | 0.21 | 18 | 315 | 0 | 190 | 0 | 0.97 | 489 |
| **12** | | 2959 | 0.10 | 308 | 87 | 0.21 | 19 | 326 | 0 | 190 | 0 | 0.97 | 499 |
| **13** | | 2959 | 0.11 | 319 | 87 | 0.22 | 19 | 338 | 0 | 190 | 0 | 0.96 | 510 |
| **14** | | 2959 | 0.11 | 332 | 87 | 0.22 | 19 | 351 | 0 | 190 | 0 | 0.96 | 520 |
| **15** | | 2959 | 0.12 | 344 | 87 | 0.23 | 20 | 364 | 196 | 190 | 0 | 0.92 | 690 |
| **16** | | 2959 | 0.12 | 357 | 87 | 0.23 | 20 | 378 | 0 | 190 | 0 | 0.92 | 520 |
| **17** | | 2959 | 0.13 | 371 | 87 | 0.24 | 21 | 392 | 0 | 190 | 0 | 0.91 | 530 |
| **18** | | 2959 | 0.13 | 385 | 87 | 0.24 | 21 | 406 | 0 | 190 | 0 | 0.91 | 540 |
| **19** | | 2959 | 0.14 | 400 | 87 | 0.25 | 22 | 421 | 0 | 190 | 0 | 0.90 | 551 |
| **20** | | 2959 | 0.14 | 415 | 87 | 0.26 | 22 | 437 | 196 | 190 | 0 | 0.85 | 695 |
| **21** | | 2959 | 0.15 | 430 | 87 | 0.26 | 23 | 453 | 0 | 190 | 0 | 0.84 | 539 |
| **22** | | 2959 | 0.15 | 447 | 87 | 0.27 | 23 | 470 | 0 | 190 | 0 | 0.83 | 549 |
| **23** | | 2959 | 0.16 | 464 | 87 | 0.27 | 24 | 487 | 0 | 190 | 0 | 0.82 | 559 |
| **24** | | 2959 | 0.16 | 481 | 87 | 0.28 | 24 | 506 | 0 | 190 | 0 | 0.82 | 569 |
| **25** | | 2959 | 0.17 | 500 | 87 | 0.28 | 25 | 524 | 196 | 190 | 0 | 0.80 | 727 |
| **26** | | 2959 | 0.18 | 519 | 87 | 0.29 | 25 | 544 | 0 | 190 | 0 | 0.79 | 581 |
| **27** | | 2959 | 0.18 | 538 | 87 | 0.30 | 26 | 564 | 0 | 190 | 0 | 0.79 | 592 |
| **28** | | 2959 | 0.19 | 559 | 87 | 0.30 | 26 | 585 | 0 | 190 | 0 | 0.78 | 603 |
| **29** | | 2959 | 0.20 | 580 | 87 | 0.31 | 27 | 607 | 0 | 190 | 0 | 0.77 | 615 |
| **30** | | 2959 | 0.20 | 602 | 87 | 0.32 | 28 | 630 | 0 | 190 | 150 | 0.76 | 512 |
| **Total** | 4,284 | 88,774 | 4 | 11,076 | 2,599 | 7 | 613 | 11,689 | 978 | 5,700 | 150 | 28 | 20,523 |

**Case 9**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,808 | | | | | | | | | | | | 3,808 |
| **1** | | 3319 | 0.07 | 229 | 139 | 0.17 | 24 | 253 | 0 | 190 | 0 | 1.00 | 419 |
| **2** | | 3319 | 0.07 | 238 | 139 | 0.17 | 24 | 262 | 0 | 190 | 0 | 1.00 | 452 |
| **3** | | 3319 | 0.07 | 247 | 139 | 0.18 | 25 | 271 | 0 | 190 | 0 | 1.00 | 461 |
| **4** | | 3319 | 0.08 | 256 | 139 | 0.18 | 25 | 281 | 0 | 190 | 0 | 1.00 | 471 |
| **5** | | 3319 | 0.08 | 266 | 139 | 0.18 | 26 | 291 | 1120 | 190 | 0 | 1.00 | 1602 |
| **6** | | 3319 | 0.08 | 276 | 139 | 0.19 | 26 | 302 | 0 | 190 | 0 | 1.00 | 492 |
| **7** | | 3319 | 0.09 | 286 | 139 | 0.19 | 27 | 313 | 0 | 190 | 0 | 1.00 | 503 |
| **8** | | 3319 | 0.09 | 297 | 139 | 0.20 | 27 | 325 | 0 | 190 | 0 | 1.00 | 515 |
| **9** | | 3319 | 0.09 | 309 | 139 | 0.20 | 28 | 337 | 0 | 190 | 0 | 1.00 | 527 |
| **10** | | 3319 | 0.10 | 320 | 139 | 0.21 | 29 | 349 | 196 | 190 | 0 | 0.97 | 714 |
| **11** | | 3319 | 0.10 | 332 | 139 | 0.21 | 29 | 362 | 0 | 190 | 0 | 0.97 | 535 |
| **12** | | 3319 | 0.10 | 345 | 139 | 0.21 | 30 | 375 | 0 | 190 | 0 | 0.97 | 546 |
| **13** | | 3319 | 0.11 | 358 | 139 | 0.22 | 31 | 389 | 0 | 190 | 0 | 0.96 | 558 |
| **14** | | 3319 | 0.11 | 372 | 139 | 0.22 | 31 | 403 | 0 | 190 | 0 | 0.96 | 570 |
| **15** | | 3319 | 0.12 | 386 | 139 | 0.23 | 32 | 418 | 196 | 190 | 0 | 0.92 | 740 |
| **16** | | 3319 | 0.12 | 401 | 139 | 0.23 | 33 | 433 | 0 | 190 | 0 | 0.92 | 571 |
| **17** | | 3319 | 0.13 | 416 | 139 | 0.24 | 33 | 449 | 0 | 190 | 0 | 0.91 | 582 |
| **18** | | 3319 | 0.13 | 432 | 139 | 0.24 | 34 | 466 | 0 | 190 | 0 | 0.91 | 594 |
| **19** | | 3319 | 0.14 | 448 | 139 | 0.25 | 35 | 483 | 0 | 190 | 0 | 0.90 | 606 |
| **20** | | 3319 | 0.14 | 465 | 139 | 0.26 | 36 | 501 | 196 | 190 | 0 | 0.85 | 749 |
| **21** | | 3319 | 0.15 | 483 | 139 | 0.26 | 36 | 519 | 0 | 190 | 0 | 0.84 | 595 |
| **22** | | 3319 | 0.15 | 501 | 139 | 0.27 | 37 | 538 | 0 | 190 | 0 | 0.83 | 606 |
| **23** | | 3319 | 0.16 | 520 | 139 | 0.27 | 38 | 558 | 0 | 190 | 0 | 0.82 | 617 |
| **24** | | 3319 | 0.16 | 540 | 139 | 0.28 | 39 | 579 | 0 | 190 | 0 | 0.82 | 629 |
| **25** | | 3319 | 0.17 | 560 | 139 | 0.28 | 40 | 600 | 1120 | 190 | 0 | 0.80 | 1527 |
| **26** | | 3319 | 0.18 | 582 | 139 | 0.29 | 41 | 622 | 0 | 190 | 0 | 0.79 | 643 |
| **27** | | 3319 | 0.18 | 604 | 139 | 0.30 | 41 | 645 | 0 | 190 | 0 | 0.79 | 656 |
| **28** | | 3319 | 0.19 | 627 | 139 | 0.30 | 42 | 669 | 0 | 190 | 0 | 0.78 | 669 |
| **29** | | 3319 | 0.20 | 651 | 139 | 0.31 | 43 | 694 | 0 | 190 | 0 | 0.77 | 682 |
| **30** | | 3319 | 0.20 | 675 | 139 | 0.32 | 44 | 720 | 0 | 190 | 0 | 0.76 | 695 |
| **Total** | 3,808 | 99,561 | 4 | 12,422 | 4,178 | 7 | 985 | 13,407 | 2,827 | 5,700 | - | 27 | 23,334 |

**Case 10**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,920 | | | | | | | | | | | | 3,920 |
| **1** | | 3304 | 0.07 | 228 | 140 | 0.17 | 24 | 252 | 0 | 190 | 0 | 1.00 | 418 |
| **2** | | 3304 | 0.07 | 237 | 140 | 0.17 | 24 | 261 | 0 | 190 | 0 | 1.00 | 451 |
| **3** | | 3304 | 0.07 | 246 | 140 | 0.18 | 25 | 270 | 0 | 190 | 0 | 1.00 | 460 |
| **4** | | 3304 | 0.08 | 255 | 140 | 0.18 | 25 | 280 | 0 | 190 | 0 | 1.00 | 470 |
| **5** | | 3304 | 0.08 | 265 | 140 | 0.18 | 26 | 290 | 1120 | 190 | 0 | 1.00 | 1601 |
| **6** | | 3304 | 0.08 | 275 | 140 | 0.19 | 26 | 301 | 0 | 190 | 0 | 1.00 | 491 |
| **7** | | 3304 | 0.09 | 285 | 140 | 0.19 | 27 | 312 | 0 | 190 | 0 | 1.00 | 502 |
| **8** | | 3304 | 0.09 | 296 | 140 | 0.20 | 28 | 324 | 0 | 190 | 0 | 1.00 | 514 |
| **9** | | 3304 | 0.09 | 307 | 140 | 0.20 | 28 | 335 | 0 | 190 | 0 | 1.00 | 525 |
| **10** | | 3304 | 0.10 | 319 | 140 | 0.21 | 29 | 348 | 196 | 190 | 0 | 0.97 | 713 |
| **11** | | 3304 | 0.10 | 331 | 140 | 0.21 | 29 | 360 | 0 | 190 | 0 | 0.97 | 534 |
| **12** | | 3304 | 0.10 | 344 | 140 | 0.21 | 30 | 374 | 0 | 190 | 0 | 0.97 | 545 |
| **13** | | 3304 | 0.11 | 357 | 140 | 0.22 | 31 | 387 | 0 | 190 | 0 | 0.96 | 557 |
| **14** | | 3304 | 0.11 | 370 | 140 | 0.22 | 31 | 402 | 0 | 190 | 0 | 0.96 | 569 |
| **15** | | 3304 | 0.12 | 384 | 140 | 0.23 | 32 | 416 | 196 | 190 | 0 | 0.92 | 739 |
| **16** | | 3304 | 0.12 | 399 | 140 | 0.23 | 33 | 432 | 0 | 190 | 0 | 0.92 | 569 |
| **17** | | 3304 | 0.13 | 414 | 140 | 0.24 | 33 | 448 | 0 | 190 | 0 | 0.91 | 581 |
| **18** | | 3304 | 0.13 | 430 | 140 | 0.24 | 34 | 464 | 0 | 190 | 0 | 0.91 | 593 |
| **19** | | 3304 | 0.14 | 446 | 140 | 0.25 | 35 | 481 | 0 | 190 | 0 | 0.90 | 605 |
| **20** | | 3304 | 0.14 | 463 | 140 | 0.26 | 36 | 499 | 196 | 190 | 0 | 0.85 | 748 |
| **21** | | 3304 | 0.15 | 481 | 140 | 0.26 | 37 | 517 | 0 | 190 | 0 | 0.84 | 593 |
| **22** | | 3304 | 0.15 | 499 | 140 | 0.27 | 37 | 536 | 0 | 190 | 0 | 0.83 | 604 |
| **23** | | 3304 | 0.16 | 518 | 140 | 0.27 | 38 | 556 | 0 | 190 | 0 | 0.82 | 615 |
| **24** | | 3304 | 0.16 | 538 | 140 | 0.28 | 39 | 577 | 0 | 190 | 0 | 0.82 | 627 |
| **25** | | 3304 | 0.17 | 558 | 140 | 0.28 | 40 | 598 | 1120 | 190 | 0 | 0.80 | 1525 |
| **26** | | 3304 | 0.18 | 579 | 140 | 0.29 | 41 | 620 | 0 | 190 | 0 | 0.79 | 642 |
| **27** | | 3304 | 0.18 | 601 | 140 | 0.30 | 42 | 643 | 0 | 190 | 0 | 0.79 | 654 |
| **28** | | 3304 | 0.19 | 624 | 140 | 0.30 | 43 | 667 | 0 | 190 | 0 | 0.78 | 667 |
| **29** | | 3304 | 0.20 | 648 | 140 | 0.31 | 43 | 691 | 0 | 190 | 0 | 0.77 | 680 |
| **30** | | 3304 | 0.20 | 672 | 140 | 0.32 | 44 | 717 | 0 | 190 | 0 | 0.76 | 693 |
| **Total** | 3,920 | 99,124 | 4 | 12,368 | 4,197 | 7 | 989 | 13,357 | 2,827 | 5,700 | - | 27 | 23,402 |

**Case 11**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,088 | | | | | | | | | | | | 4,088 |
| **1** | | 3298 | 0.07 | 228 | 140 | 0.17 | 24 | 251 | 0 | 190 | 0 | 1.00 | 418 |
| **2** | | 3298 | 0.07 | 236 | 140 | 0.17 | 24 | 260 | 0 | 190 | 0 | 1.00 | 450 |
| **3** | | 3298 | 0.07 | 245 | 140 | 0.18 | 25 | 270 | 0 | 190 | 0 | 1.00 | 460 |
| **4** | | 3298 | 0.08 | 255 | 140 | 0.18 | 25 | 280 | 0 | 190 | 0 | 1.00 | 470 |
| **5** | | 3298 | 0.08 | 264 | 140 | 0.18 | 26 | 290 | 1120 | 190 | 0 | 1.00 | 1600 |
| **6** | | 3298 | 0.08 | 274 | 140 | 0.19 | 26 | 301 | 0 | 190 | 0 | 1.00 | 491 |
| **7** | | 3298 | 0.09 | 285 | 140 | 0.19 | 27 | 312 | 0 | 190 | 0 | 1.00 | 502 |
| **8** | | 3298 | 0.09 | 295 | 140 | 0.20 | 28 | 323 | 0 | 190 | 0 | 1.00 | 513 |
| **9** | | 3298 | 0.09 | 307 | 140 | 0.20 | 28 | 335 | 0 | 190 | 0 | 1.00 | 525 |
| **10** | | 3298 | 0.10 | 318 | 140 | 0.21 | 29 | 347 | 196 | 190 | 0 | 0.97 | 713 |
| **11** | | 3298 | 0.10 | 330 | 140 | 0.21 | 29 | 360 | 0 | 190 | 0 | 0.97 | 533 |
| **12** | | 3298 | 0.10 | 343 | 140 | 0.21 | 30 | 373 | 0 | 190 | 0 | 0.97 | 545 |
| **13** | | 3298 | 0.11 | 356 | 140 | 0.22 | 31 | 387 | 0 | 190 | 0 | 0.96 | 556 |
| **14** | | 3298 | 0.11 | 370 | 140 | 0.22 | 31 | 401 | 0 | 190 | 0 | 0.96 | 568 |
| **15** | | 3298 | 0.12 | 384 | 140 | 0.23 | 32 | 416 | 196 | 190 | 0 | 0.92 | 738 |
| **16** | | 3298 | 0.12 | 398 | 140 | 0.23 | 33 | 431 | 0 | 190 | 0 | 0.92 | 569 |
| **17** | | 3298 | 0.13 | 413 | 140 | 0.24 | 34 | 447 | 0 | 190 | 0 | 0.91 | 580 |
| **18** | | 3298 | 0.13 | 429 | 140 | 0.24 | 34 | 463 | 0 | 190 | 0 | 0.91 | 592 |
| **19** | | 3298 | 0.14 | 445 | 140 | 0.25 | 35 | 480 | 0 | 190 | 0 | 0.90 | 604 |
| **20** | | 3298 | 0.14 | 462 | 140 | 0.26 | 36 | 498 | 196 | 190 | 0 | 0.85 | 747 |
| **21** | | 3298 | 0.15 | 480 | 140 | 0.26 | 37 | 516 | 0 | 190 | 0 | 0.84 | 592 |
| **22** | | 3298 | 0.15 | 498 | 140 | 0.27 | 37 | 535 | 0 | 190 | 0 | 0.83 | 603 |
| **23** | | 3298 | 0.16 | 517 | 140 | 0.27 | 38 | 555 | 0 | 190 | 0 | 0.82 | 614 |
| **24** | | 3298 | 0.16 | 537 | 140 | 0.28 | 39 | 576 | 0 | 190 | 0 | 0.82 | 626 |
| **25** | | 3298 | 0.17 | 557 | 140 | 0.28 | 40 | 597 | 1120 | 190 | 0 | 0.80 | 1524 |
| **26** | | 3298 | 0.18 | 578 | 140 | 0.29 | 41 | 619 | 0 | 190 | 0 | 0.79 | 641 |
| **27** | | 3298 | 0.18 | 600 | 140 | 0.30 | 42 | 642 | 0 | 190 | 0 | 0.79 | 653 |
| **28** | | 3298 | 0.19 | 623 | 140 | 0.30 | 43 | 666 | 0 | 190 | 0 | 0.78 | 666 |
| **29** | | 3298 | 0.20 | 647 | 140 | 0.31 | 44 | 690 | 0 | 190 | 0 | 0.77 | 679 |
| **30** | | 3298 | 0.20 | 671 | 140 | 0.32 | 45 | 716 | 0 | 190 | 0 | 0.76 | 692 |
| **Total** | 4,088 | 98,948 | 4 | 12,346 | 4,205 | 7 | 991 | 13,337 | 2,827 | 5,700 | - | 27 | 23,552 |

**Case 12**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,320 | | | | | | | | | | | | 3,320 |
| **1** | | 3473 | 0.07 | 240 | 130 | 0.17 | 22 | 262 | 0 | 140 | 0 | 1.00 | 380 |
| **2** | | 3473 | 0.07 | 249 | 130 | 0.17 | 22 | 271 | 0 | 140 | 0 | 1.00 | 411 |
| **3** | | 3473 | 0.07 | 258 | 130 | 0.18 | 23 | 281 | 0 | 140 | 0 | 1.00 | 421 |
| **4** | | 3473 | 0.08 | 268 | 130 | 0.18 | 23 | 291 | 0 | 140 | 0 | 1.00 | 431 |
| **5** | | 3473 | 0.08 | 278 | 130 | 0.18 | 24 | 302 | 1120 | 140 | 0 | 1.00 | 1562 |
| **6** | | 3473 | 0.08 | 289 | 130 | 0.19 | 25 | 313 | 0 | 140 | 0 | 1.00 | 453 |
| **7** | | 3473 | 0.09 | 300 | 130 | 0.19 | 25 | 325 | 0 | 140 | 0 | 1.00 | 465 |
| **8** | | 3473 | 0.09 | 311 | 130 | 0.20 | 26 | 337 | 0 | 140 | 0 | 1.00 | 477 |
| **9** | | 3473 | 0.09 | 323 | 130 | 0.20 | 26 | 349 | 0 | 140 | 0 | 1.00 | 489 |
| **10** | | 3473 | 0.10 | 335 | 130 | 0.21 | 27 | 362 | 196 | 140 | 0 | 0.97 | 678 |
| **11** | | 3473 | 0.10 | 348 | 130 | 0.21 | 27 | 375 | 0 | 140 | 0 | 0.97 | 500 |
| **12** | | 3473 | 0.10 | 361 | 130 | 0.21 | 28 | 389 | 0 | 140 | 0 | 0.97 | 512 |
| **13** | | 3473 | 0.11 | 375 | 130 | 0.22 | 29 | 403 | 0 | 140 | 0 | 0.96 | 524 |
| **14** | | 3473 | 0.11 | 389 | 130 | 0.22 | 29 | 418 | 0 | 140 | 0 | 0.96 | 537 |
| **15** | | 3473 | 0.12 | 404 | 130 | 0.23 | 30 | 434 | 196 | 140 | 0 | 0.92 | 709 |
| **16** | | 3473 | 0.12 | 419 | 130 | 0.23 | 30 | 450 | 0 | 140 | 0 | 0.92 | 540 |
| **17** | | 3473 | 0.13 | 435 | 130 | 0.24 | 31 | 466 | 0 | 140 | 0 | 0.91 | 552 |
| **18** | | 3473 | 0.13 | 452 | 130 | 0.24 | 32 | 484 | 0 | 140 | 0 | 0.91 | 565 |
| **19** | | 3473 | 0.14 | 469 | 130 | 0.25 | 33 | 501 | 0 | 140 | 0 | 0.90 | 578 |
| **20** | | 3473 | 0.14 | 487 | 130 | 0.26 | 33 | 520 | 196 | 140 | 0 | 0.85 | 724 |
| **21** | | 3473 | 0.15 | 505 | 130 | 0.26 | 34 | 539 | 0 | 140 | 0 | 0.84 | 570 |
| **22** | | 3473 | 0.15 | 524 | 130 | 0.27 | 35 | 559 | 0 | 140 | 0 | 0.83 | 581 |
| **23** | | 3473 | 0.16 | 544 | 130 | 0.27 | 35 | 580 | 0 | 140 | 0 | 0.82 | 594 |
| **24** | | 3473 | 0.16 | 565 | 130 | 0.28 | 36 | 601 | 0 | 140 | 0 | 0.82 | 606 |
| **25** | | 3473 | 0.17 | 587 | 130 | 0.28 | 37 | 624 | 1120 | 140 | 0 | 0.80 | 1506 |
| **26** | | 3473 | 0.18 | 609 | 130 | 0.29 | 38 | 647 | 0 | 140 | 0 | 0.79 | 623 |
| **27** | | 3473 | 0.18 | 632 | 130 | 0.30 | 39 | 671 | 0 | 140 | 0 | 0.79 | 636 |
| **28** | | 3473 | 0.19 | 656 | 130 | 0.30 | 40 | 696 | 0 | 140 | 0 | 0.78 | 650 |
| **29** | | 3473 | 0.20 | 681 | 130 | 0.31 | 40 | 721 | 0 | 140 | 0 | 0.77 | 664 |
| **30** | | 3473 | 0.20 | 707 | 130 | 0.32 | 41 | 748 | 0 | 140 | 0 | 0.76 | 679 |
| **Total** | 3,320 | 104,198 | 4 | 13,001 | 3,903 | 7 | 920 | 13,921 | 2,827 | 4,200 | - | 27 | 21,938 |

**Case 13**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,150 | | | | | | | | | | | | 4,150 |
| **1** | | 3464 | 0.07 | 239 | 129 | 0.17 | 22 | 261 | 0 | 140 | 0 | 1.00 | 379 |
| **2** | | 3464 | 0.07 | 248 | 129 | 0.17 | 22 | 270 | 0 | 140 | 0 | 1.00 | 410 |
| **3** | | 3464 | 0.07 | 258 | 129 | 0.18 | 23 | 280 | 0 | 140 | 0 | 1.00 | 420 |
| **4** | | 3464 | 0.08 | 267 | 129 | 0.18 | 23 | 291 | 0 | 140 | 0 | 1.00 | 431 |
| **5** | | 3464 | 0.08 | 277 | 129 | 0.18 | 24 | 301 | 1120 | 140 | 0 | 1.00 | 1561 |
| **6** | | 3464 | 0.08 | 288 | 129 | 0.19 | 24 | 312 | 0 | 140 | 0 | 1.00 | 452 |
| **7** | | 3464 | 0.09 | 299 | 129 | 0.19 | 25 | 324 | 0 | 140 | 0 | 1.00 | 464 |
| **8** | | 3464 | 0.09 | 310 | 129 | 0.20 | 25 | 336 | 0 | 140 | 0 | 1.00 | 476 |
| **9** | | 3464 | 0.09 | 322 | 129 | 0.20 | 26 | 348 | 0 | 140 | 0 | 1.00 | 488 |
| **10** | | 3464 | 0.10 | 334 | 129 | 0.21 | 26 | 361 | 196 | 140 | 0 | 0.97 | 677 |
| **11** | | 3464 | 0.10 | 347 | 129 | 0.21 | 27 | 374 | 0 | 140 | 0 | 0.97 | 499 |
| **12** | | 3464 | 0.10 | 360 | 129 | 0.21 | 28 | 388 | 0 | 140 | 0 | 0.97 | 510 |
| **13** | | 3464 | 0.11 | 374 | 129 | 0.22 | 28 | 402 | 0 | 140 | 0 | 0.96 | 523 |
| **14** | | 3464 | 0.11 | 388 | 129 | 0.22 | 29 | 417 | 0 | 140 | 0 | 0.96 | 536 |
| **15** | | 3464 | 0.12 | 403 | 129 | 0.23 | 29 | 432 | 196 | 140 | 0 | 0.92 | 707 |
| **16** | | 3464 | 0.12 | 418 | 129 | 0.23 | 30 | 448 | 0 | 140 | 0 | 0.92 | 539 |
| **17** | | 3464 | 0.13 | 434 | 129 | 0.24 | 31 | 465 | 0 | 140 | 0 | 0.91 | 551 |
| **18** | | 3464 | 0.13 | 451 | 129 | 0.24 | 31 | 482 | 0 | 140 | 0 | 0.91 | 564 |
| **19** | | 3464 | 0.14 | 468 | 129 | 0.25 | 32 | 500 | 0 | 140 | 0 | 0.90 | 577 |
| **20** | | 3464 | 0.14 | 486 | 129 | 0.26 | 33 | 518 | 196 | 140 | 0 | 0.85 | 722 |
| **21** | | 3464 | 0.15 | 504 | 129 | 0.26 | 34 | 538 | 0 | 140 | 0 | 0.84 | 568 |
| **22** | | 3464 | 0.15 | 523 | 129 | 0.27 | 34 | 557 | 0 | 140 | 0 | 0.83 | 580 |
| **23** | | 3464 | 0.16 | 543 | 129 | 0.27 | 35 | 578 | 0 | 140 | 0 | 0.82 | 592 |
| **24** | | 3464 | 0.16 | 564 | 129 | 0.28 | 36 | 599 | 0 | 140 | 0 | 0.82 | 605 |
| **25** | | 3464 | 0.17 | 585 | 129 | 0.28 | 37 | 622 | 1120 | 140 | 0 | 0.80 | 1504 |
| **26** | | 3464 | 0.18 | 607 | 129 | 0.29 | 37 | 645 | 0 | 140 | 0 | 0.79 | 622 |
| **27** | | 3464 | 0.18 | 630 | 129 | 0.30 | 38 | 669 | 0 | 140 | 0 | 0.79 | 635 |
| **28** | | 3464 | 0.19 | 654 | 129 | 0.30 | 39 | 693 | 0 | 140 | 0 | 0.78 | 649 |
| **29** | | 3464 | 0.20 | 679 | 129 | 0.31 | 40 | 719 | 0 | 140 | 0 | 0.77 | 663 |
| **30** | | 3464 | 0.20 | 705 | 129 | 0.32 | 41 | 746 | 0 | 140 | 0 | 0.76 | 677 |
| **Total** | 4,150 | 103,930 | 4 | 12,967 | 3,857 | 7 | 909 | 13,877 | 2,827 | 4,200 | - | 27 | 22,729 |

**Case 14**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,980 | | | | | | | | | | | | 4,980 |
| **1** | | 3450 | 0.07 | 238 | 128 | 0.17 | 22 | 260 | 0 | 140 | 0 | 1.00 | 378 |
| **2** | | 3450 | 0.07 | 247 | 128 | 0.17 | 22 | 269 | 0 | 140 | 0 | 1.00 | 409 |
| **3** | | 3450 | 0.07 | 257 | 128 | 0.18 | 23 | 279 | 0 | 140 | 0 | 1.00 | 419 |
| **4** | | 3450 | 0.08 | 266 | 128 | 0.18 | 23 | 289 | 0 | 140 | 0 | 1.00 | 429 |
| **5** | | 3450 | 0.08 | 276 | 128 | 0.18 | 24 | 300 | 1120 | 140 | 0 | 1.00 | 1560 |
| **6** | | 3450 | 0.08 | 287 | 128 | 0.19 | 24 | 311 | 0 | 140 | 0 | 1.00 | 451 |
| **7** | | 3450 | 0.09 | 298 | 128 | 0.19 | 25 | 323 | 0 | 140 | 0 | 1.00 | 463 |
| **8** | | 3450 | 0.09 | 309 | 128 | 0.20 | 25 | 334 | 0 | 140 | 0 | 1.00 | 474 |
| **9** | | 3450 | 0.09 | 321 | 128 | 0.20 | 26 | 347 | 0 | 140 | 0 | 1.00 | 487 |
| **10** | | 3450 | 0.10 | 333 | 128 | 0.21 | 26 | 359 | 196 | 140 | 0 | 0.97 | 676 |
| **11** | | 3450 | 0.10 | 346 | 128 | 0.21 | 27 | 373 | 0 | 140 | 0 | 0.97 | 497 |
| **12** | | 3450 | 0.10 | 359 | 128 | 0.21 | 28 | 386 | 0 | 140 | 0 | 0.97 | 509 |
| **13** | | 3450 | 0.11 | 372 | 128 | 0.22 | 28 | 401 | 0 | 140 | 0 | 0.96 | 521 |
| **14** | | 3450 | 0.11 | 387 | 128 | 0.22 | 29 | 415 | 0 | 140 | 0 | 0.96 | 534 |
| **15** | | 3450 | 0.12 | 401 | 128 | 0.23 | 29 | 431 | 196 | 140 | 0 | 0.92 | 706 |
| **16** | | 3450 | 0.12 | 417 | 128 | 0.23 | 30 | 447 | 0 | 140 | 0 | 0.92 | 537 |
| **17** | | 3450 | 0.13 | 432 | 128 | 0.24 | 31 | 463 | 0 | 140 | 0 | 0.91 | 549 |
| **18** | | 3450 | 0.13 | 449 | 128 | 0.24 | 31 | 480 | 0 | 140 | 0 | 0.91 | 562 |
| **19** | | 3450 | 0.14 | 466 | 128 | 0.25 | 32 | 498 | 0 | 140 | 0 | 0.90 | 575 |
| **20** | | 3450 | 0.14 | 484 | 128 | 0.26 | 33 | 516 | 196 | 140 | 0 | 0.85 | 720 |
| **21** | | 3450 | 0.15 | 502 | 128 | 0.26 | 34 | 535 | 0 | 140 | 0 | 0.84 | 566 |
| **22** | | 3450 | 0.15 | 521 | 128 | 0.27 | 34 | 555 | 0 | 140 | 0 | 0.83 | 578 |
| **23** | | 3450 | 0.16 | 541 | 128 | 0.27 | 35 | 576 | 0 | 140 | 0 | 0.82 | 590 |
| **24** | | 3450 | 0.16 | 561 | 128 | 0.28 | 36 | 597 | 0 | 140 | 0 | 0.82 | 603 |
| **25** | | 3450 | 0.17 | 583 | 128 | 0.28 | 37 | 619 | 1120 | 140 | 0 | 0.80 | 1502 |
| **26** | | 3450 | 0.18 | 605 | 128 | 0.29 | 37 | 642 | 0 | 140 | 0 | 0.79 | 620 |
| **27** | | 3450 | 0.18 | 628 | 128 | 0.30 | 38 | 666 | 0 | 140 | 0 | 0.79 | 633 |
| **28** | | 3450 | 0.19 | 652 | 128 | 0.30 | 39 | 691 | 0 | 140 | 0 | 0.78 | 646 |
| **29** | | 3450 | 0.20 | 676 | 128 | 0.31 | 40 | 716 | 0 | 140 | 0 | 0.77 | 660 |
| **30** | | 3450 | 0.20 | 702 | 128 | 0.32 | 41 | 743 | 0 | 140 | 0 | 0.76 | 675 |
| **Total** | 4,980 | 103,510 | 4 | 12,915 | 3,855 | 7 | 909 | 13,823 | 2,827 | 4,200 | - | 27 | 23,512 |

**Case 15**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 5,810 | | | | | | | | | | | | 5,810 |
| **1** | | 3462 | 0.07 | 239 | 127 | 0.17 | 21 | 260 | 0 | 140 | 0 | 1.00 | 379 |
| **2** | | 3462 | 0.07 | 248 | 127 | 0.17 | 22 | 270 | 0 | 140 | 0 | 1.00 | 410 |
| **3** | | 3462 | 0.07 | 257 | 127 | 0.18 | 22 | 280 | 0 | 140 | 0 | 1.00 | 420 |
| **4** | | 3462 | 0.08 | 267 | 127 | 0.18 | 23 | 290 | 0 | 140 | 0 | 1.00 | 430 |
| **5** | | 3462 | 0.08 | 277 | 127 | 0.18 | 23 | 301 | 1120 | 140 | 0 | 1.00 | 1561 |
| **6** | | 3462 | 0.08 | 288 | 127 | 0.19 | 24 | 312 | 0 | 140 | 0 | 1.00 | 452 |
| **7** | | 3462 | 0.09 | 299 | 127 | 0.19 | 24 | 323 | 0 | 140 | 0 | 1.00 | 463 |
| **8** | | 3462 | 0.09 | 310 | 127 | 0.20 | 25 | 335 | 0 | 140 | 0 | 1.00 | 475 |
| **9** | | 3462 | 0.09 | 322 | 127 | 0.20 | 26 | 347 | 0 | 140 | 0 | 1.00 | 487 |
| **10** | | 3462 | 0.10 | 334 | 127 | 0.21 | 26 | 360 | 196 | 140 | 0 | 0.97 | 677 |
| **11** | | 3462 | 0.10 | 347 | 127 | 0.21 | 27 | 374 | 0 | 140 | 0 | 0.97 | 498 |
| **12** | | 3462 | 0.10 | 360 | 127 | 0.21 | 27 | 387 | 0 | 140 | 0 | 0.97 | 510 |
| **13** | | 3462 | 0.11 | 374 | 127 | 0.22 | 28 | 402 | 0 | 140 | 0 | 0.96 | 522 |
| **14** | | 3462 | 0.11 | 388 | 127 | 0.22 | 28 | 416 | 0 | 140 | 0 | 0.96 | 535 |
| **15** | | 3462 | 0.12 | 403 | 127 | 0.23 | 29 | 432 | 196 | 140 | 0 | 0.92 | 707 |
| **16** | | 3462 | 0.12 | 418 | 127 | 0.23 | 30 | 448 | 0 | 140 | 0 | 0.92 | 538 |
| **17** | | 3462 | 0.13 | 434 | 127 | 0.24 | 30 | 464 | 0 | 140 | 0 | 0.91 | 550 |
| **18** | | 3462 | 0.13 | 450 | 127 | 0.24 | 31 | 481 | 0 | 140 | 0 | 0.91 | 563 |
| **19** | | 3462 | 0.14 | 467 | 127 | 0.25 | 32 | 499 | 0 | 140 | 0 | 0.90 | 576 |
| **20** | | 3462 | 0.14 | 485 | 127 | 0.26 | 32 | 518 | 196 | 140 | 0 | 0.85 | 721 |
| **21** | | 3462 | 0.15 | 504 | 127 | 0.26 | 33 | 537 | 0 | 140 | 0 | 0.84 | 568 |
| **22** | | 3462 | 0.15 | 523 | 127 | 0.27 | 34 | 557 | 0 | 140 | 0 | 0.83 | 579 |
| **23** | | 3462 | 0.16 | 543 | 127 | 0.27 | 35 | 577 | 0 | 140 | 0 | 0.82 | 591 |
| **24** | | 3462 | 0.16 | 563 | 127 | 0.28 | 35 | 599 | 0 | 140 | 0 | 0.82 | 604 |
| **25** | | 3462 | 0.17 | 585 | 127 | 0.28 | 36 | 621 | 1120 | 140 | 0 | 0.80 | 1503 |
| **26** | | 3462 | 0.18 | 607 | 127 | 0.29 | 37 | 644 | 0 | 140 | 0 | 0.79 | 621 |
| **27** | | 3462 | 0.18 | 630 | 127 | 0.30 | 38 | 668 | 0 | 140 | 0 | 0.79 | 634 |
| **28** | | 3462 | 0.19 | 654 | 127 | 0.30 | 39 | 692 | 0 | 140 | 0 | 0.78 | 648 |
| **29** | | 3462 | 0.20 | 679 | 127 | 0.31 | 39 | 718 | 0 | 140 | 0 | 0.77 | 662 |
| **30** | | 3462 | 0.20 | 704 | 127 | 0.32 | 40 | 745 | 0 | 140 | 0 | 0.76 | 676 |
| | | | | | | | | | | | | | 0.00 |
| **Total** | 5,810 | 103,852 | 4 | 12,958 | 3,811 | 7 | 898 | 13,856 | 2,827 | 4,200 | - | 27 | 24,371 |

**Case 17**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,000 | | | | | | | | | | | | 1,000 |
| **1** | | 3455 | 0.07 | 238 | 112 | 0.17 | 19 | 257 | 0 | 230 | 0 | 1.00 | 468 |
| **2** | | 3455 | 0.07 | 247 | 112 | 0.17 | 19 | 267 | 0 | 230 | 0 | 1.00 | 497 |
| **3** | | 3455 | 0.07 | 257 | 112 | 0.18 | 20 | 277 | 0 | 230 | 0 | 1.00 | 507 |
| **4** | | 3455 | 0.08 | 267 | 112 | 0.18 | 20 | 287 | 0 | 230 | 0 | 1.00 | 517 |
| **5** | | 3455 | 0.08 | 277 | 112 | 0.18 | 21 | 297 | 1120 | 230 | 0 | 1.00 | 1648 |
| **6** | | 3455 | 0.08 | 287 | 112 | 0.19 | 21 | 308 | 0 | 230 | 0 | 1.00 | 538 |
| **7** | | 3455 | 0.09 | 298 | 112 | 0.19 | 22 | 320 | 0 | 230 | 0 | 1.00 | 550 |
| **8** | | 3455 | 0.09 | 310 | 112 | 0.20 | 22 | 332 | 0 | 230 | 0 | 1.00 | 562 |
| **9** | | 3455 | 0.09 | 321 | 112 | 0.20 | 22 | 344 | 0 | 230 | 0 | 1.00 | 574 |
| **10** | | 3455 | 0.10 | 334 | 112 | 0.21 | 23 | 356 | 196 | 230 | 0 | 0.97 | 761 |
| **11** | | 3455 | 0.10 | 346 | 112 | 0.21 | 23 | 370 | 0 | 230 | 0 | 0.97 | 581 |
| **12** | | 3455 | 0.10 | 359 | 112 | 0.21 | 24 | 383 | 0 | 230 | 0 | 0.97 | 593 |
| **13** | | 3455 | 0.11 | 373 | 112 | 0.22 | 25 | 398 | 0 | 230 | 0 | 0.96 | 605 |
| **14** | | 3455 | 0.11 | 387 | 112 | 0.22 | 25 | 412 | 0 | 230 | 0 | 0.96 | 618 |
| **15** | | 3455 | 0.12 | 402 | 112 | 0.23 | 26 | 427 | 196 | 230 | 0 | 0.92 | 786 |
| **16** | | 3455 | 0.12 | 417 | 112 | 0.23 | 26 | 443 | 0 | 230 | 0 | 0.92 | 617 |
| **17** | | 3455 | 0.13 | 433 | 112 | 0.24 | 27 | 460 | 0 | 230 | 0 | 0.91 | 628 |
| **18** | | 3455 | 0.13 | 449 | 112 | 0.24 | 27 | 477 | 0 | 230 | 0 | 0.91 | 640 |
| **19** | | 3455 | 0.14 | 467 | 112 | 0.25 | 28 | 494 | 0 | 230 | 0 | 0.90 | 653 |
| **20** | | 3455 | 0.14 | 484 | 112 | 0.26 | 29 | 513 | 1196 | 230 | 0 | 0.85 | 1639 |
| **21** | | 3455 | 0.15 | 503 | 112 | 0.26 | 29 | 532 | 0 | 230 | 0 | 0.84 | 639 |
| **22** | | 3455 | 0.15 | 522 | 112 | 0.27 | 30 | 552 | 0 | 230 | 0 | 0.83 | 650 |
| **23** | | 3455 | 0.16 | 542 | 112 | 0.27 | 30 | 572 | 0 | 230 | 0 | 0.82 | 661 |
| **24** | | 3455 | 0.16 | 562 | 112 | 0.28 | 31 | 593 | 0 | 230 | 0 | 0.82 | 673 |
| **25** | | 3455 | 0.17 | 584 | 112 | 0.28 | 32 | 615 | 1120 | 230 | 0 | 0.80 | 1571 |
| **26** | | 3455 | 0.18 | 606 | 112 | 0.29 | 33 | 638 | 0 | 230 | 0 | 0.79 | 688 |
| **27** | | 3455 | 0.18 | 629 | 112 | 0.30 | 33 | 662 | 0 | 230 | 0 | 0.79 | 700 |
| **28** | | 3455 | 0.19 | 653 | 112 | 0.30 | 34 | 687 | 0 | 230 | 0 | 0.78 | 713 |
| **29** | | 3455 | 0.20 | 677 | 112 | 0.31 | 35 | 712 | 0 | 230 | 0 | 0.77 | 727 |
| **30** | | 3455 | 0.20 | 703 | 112 | 0.32 | 35 | 739 | 0 | 230 | 245 | 0.76 | 553 |
| **Total** | 1,000 | 103,663 | 4 | 12,934 | 3,352 | 7 | 790 | 13,724 | 3,827 | 6,900 | 245 | 27 | 22,556 |

**Case 18**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,000 | | | | | | | | | | | | 1000 |
| **1** | | 3455 | 0.07 | 238 | 107 | 0.17 | 18 | 257 | 0 | 230 | 0 | 1.00 | 468 |
| **2** | | 3455 | 0.07 | 247 | 107 | 0.17 | 19 | 266 | 0 | 230 | 0 | 1.00 | 496 |
| **3** | | 3455 | 0.07 | 257 | 107 | 0.18 | 19 | 276 | 0 | 230 | 0 | 1.00 | 506 |
| **4** | | 3455 | 0.08 | 267 | 107 | 0.18 | 19 | 286 | 0 | 230 | 0 | 1.00 | 516 |
| **5** | | 3455 | 0.08 | 277 | 107 | 0.18 | 20 | 297 | 1120 | 230 | 0 | 1.00 | 1647 |
| **6** | | 3455 | 0.08 | 287 | 107 | 0.19 | 20 | 307 | 0 | 230 | 0 | 1.00 | 537 |
| **7** | | 3455 | 0.09 | 298 | 107 | 0.19 | 21 | 319 | 0 | 230 | 0 | 1.00 | 549 |
| **8** | | 3455 | 0.09 | 310 | 107 | 0.20 | 21 | 331 | 0 | 230 | 0 | 1.00 | 561 |
| **9** | | 3455 | 0.09 | 321 | 107 | 0.20 | 22 | 343 | 0 | 230 | 0 | 1.00 | 573 |
| **10** | | 3455 | 0.10 | 334 | 107 | 0.21 | 22 | 356 | 196 | 230 | 0 | 0.97 | 760 |
| **11** | | 3455 | 0.10 | 346 | 107 | 0.21 | 23 | 369 | 0 | 230 | 0 | 0.97 | 581 |
| **12** | | 3455 | 0.10 | 359 | 107 | 0.21 | 23 | 382 | 0 | 230 | 0 | 0.97 | 592 |
| **13** | | 3455 | 0.11 | 373 | 107 | 0.22 | 24 | 397 | 0 | 230 | 0 | 0.96 | 604 |
| **14** | | 3455 | 0.11 | 387 | 107 | 0.22 | 24 | 411 | 0 | 230 | 0 | 0.96 | 617 |
| **15** | | 3455 | 0.12 | 402 | 107 | 0.23 | 25 | 426 | 196 | 230 | 0 | 0.92 | 785 |
| **16** | | 3455 | 0.12 | 417 | 107 | 0.23 | 25 | 442 | 0 | 230 | 0 | 0.92 | 616 |
| **17** | | 3455 | 0.13 | 433 | 107 | 0.24 | 26 | 459 | 0 | 230 | 0 | 0.91 | 627 |
| **18** | | 3455 | 0.13 | 449 | 107 | 0.24 | 26 | 476 | 0 | 230 | 0 | 0.91 | 639 |
| **19** | | 3455 | 0.14 | 467 | 107 | 0.25 | 27 | 493 | 0 | 230 | 0 | 0.90 | 652 |
| **20** | | 3455 | 0.14 | 484 | 107 | 0.26 | 27 | 512 | 1196 | 230 | 0 | 0.85 | 1638 |
| **21** | | 3455 | 0.15 | 503 | 107 | 0.26 | 28 | 531 | 0 | 230 | 0 | 0.84 | 638 |
| **22** | | 3455 | 0.15 | 522 | 107 | 0.27 | 29 | 550 | 0 | 230 | 0 | 0.83 | 649 |
| **23** | | 3455 | 0.16 | 542 | 107 | 0.27 | 29 | 571 | 0 | 230 | 0 | 0.82 | 660 |
| **24** | | 3455 | 0.16 | 562 | 107 | 0.28 | 30 | 592 | 0 | 230 | 0 | 0.82 | 672 |
| **25** | | 3455 | 0.17 | 584 | 107 | 0.28 | 31 | 614 | 1120 | 230 | 0 | 0.80 | 1570 |
| **26** | | 3455 | 0.18 | 606 | 107 | 0.29 | 31 | 637 | 0 | 230 | 0 | 0.79 | 687 |
| **27** | | 3455 | 0.18 | 629 | 107 | 0.30 | 32 | 661 | 0 | 230 | 0 | 0.79 | 699 |
| **28** | | 3455 | 0.19 | 653 | 107 | 0.30 | 33 | 685 | 0 | 230 | 0 | 0.78 | 712 |
| **29** | | 3455 | 0.20 | 677 | 107 | 0.31 | 33 | 711 | 0 | 230 | 0 | 0.77 | 725 |
| **30** | | 3455 | 0.20 | 703 | 107 | 0.32 | 34 | 737 | 0 | 230 | 245 | 0.76 | 552 |
| | | | | | | | | | | 230 | | | 0.00 |
| **Total** | 1,000 | 103,663 | 4 | 12,934 | 3,215 | 7 | 758 | 13,692 | 3,827 | 6,900 | 245 | 27 | 22,528 |

**Case 20**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,250 | | | | | | | | | | | | 1,250 |
| **1** | | 3670 | 0.07 | 253 | 137 | 0.17 | 23 | 276 | 0 | 240 | 0 | 1.00 | 493 |
| **2** | | 3670 | 0.07 | 263 | 137 | 0.17 | 24 | 286 | 0 | 240 | 0 | 1.00 | 526 |
| **3** | | 3670 | 0.07 | 273 | 137 | 0.18 | 24 | 297 | 0 | 240 | 0 | 1.00 | 537 |
| **4** | | 3670 | 0.08 | 283 | 137 | 0.18 | 25 | 308 | 0 | 240 | 0 | 1.00 | 548 |
| **5** | | 3670 | 0.08 | 294 | 137 | 0.18 | 25 | 319 | 1120 | 240 | 0 | 1.00 | 1679 |
| **6** | | 3670 | 0.08 | 305 | 137 | 0.19 | 26 | 331 | 0 | 240 | 0 | 1.00 | 571 |
| **7** | | 3670 | 0.09 | 317 | 137 | 0.19 | 26 | 343 | 0 | 240 | 0 | 1.00 | 583 |
| **8** | | 3670 | 0.09 | 329 | 137 | 0.20 | 27 | 356 | 0 | 240 | 0 | 1.00 | 596 |
| **9** | | 3670 | 0.09 | 341 | 137 | 0.20 | 28 | 369 | 0 | 240 | 0 | 1.00 | 609 |
| **10** | | 3670 | 0.10 | 354 | 137 | 0.21 | 28 | 382 | 196 | 240 | 0 | 0.97 | 795 |
| **11** | | 3670 | 0.10 | 368 | 137 | 0.21 | 29 | 396 | 0 | 240 | 0 | 0.97 | 617 |
| **12** | | 3670 | 0.10 | 382 | 137 | 0.21 | 29 | 411 | 0 | 240 | 0 | 0.97 | 630 |
| **13** | | 3670 | 0.11 | 396 | 137 | 0.22 | 30 | 426 | 0 | 240 | 0 | 0.96 | 642 |
| **14** | | 3670 | 0.11 | 411 | 137 | 0.22 | 31 | 442 | 0 | 240 | 0 | 0.96 | 656 |
| **15** | | 3670 | 0.12 | 427 | 137 | 0.23 | 31 | 458 | | 240 | 0 | 0.92 | 643 |
| **16** | | 3670 | 0.12 | 443 | 137 | 0.23 | 32 | 475 | 0 | 240 | 0 | 0.92 | 655 |
| **17** | | 3670 | 0.13 | 460 | 137 | 0.24 | 33 | 493 | 0 | 240 | 0 | 0.91 | 667 |
| **18** | | 3670 | 0.13 | 477 | 137 | 0.24 | 34 | 511 | 0 | 240 | 0 | 0.91 | 680 |
| **19** | | 3670 | 0.14 | 495 | 137 | 0.25 | 34 | 530 | 0 | 240 | 0 | 0.90 | 694 |
| **20** | | 3670 | 0.14 | 514 | 137 | 0.26 | 35 | 549 | 196 | 240 | 0 | 0.85 | 833 |
| **21** | | 3670 | 0.15 | 534 | 137 | 0.26 | 36 | 570 | 0 | 240 | 0 | 0.84 | 679 |
| **22** | | 3670 | 0.15 | 554 | 137 | 0.27 | 37 | 591 | 0 | 240 | 0 | 0.83 | 691 |
| **23** | | 3670 | 0.16 | 575 | 137 | 0.27 | 37 | 613 | 0 | 240 | 0 | 0.82 | 703 |
| **24** | | 3670 | 0.16 | 597 | 137 | 0.28 | 38 | 635 | 0 | 240 | 0 | 0.82 | 716 |
| **25** | | 3670 | 0.17 | 620 | 137 | 0.28 | 39 | 659 | 1120 | 240 | 0 | 0.80 | 1614 |
| **26** | | 3670 | 0.18 | 643 | 137 | 0.29 | 40 | 683 | 0 | 240 | 0 | 0.79 | 731 |
| **27** | | 3670 | 0.18 | 668 | 137 | 0.30 | 41 | 709 | 0 | 240 | 0 | 0.79 | 745 |
| **28** | | 3670 | 0.19 | 693 | 137 | 0.30 | 42 | 735 | 0 | 240 | 0 | 0.78 | 759 |
| **29** | | 3670 | 0.20 | 719 | 137 | 0.31 | 43 | 762 | 0 | 240 | 0 | 0.77 | 773 |
| **30** | | 3670 | 0.20 | 747 | 137 | 0.32 | 44 | 790 | 0 | 240 | 0 | 0.76 | 787 |
| **Total** | 1,250 | 110,093 | 4 | 13,736 | 4,111 | 7 | 969 | 14,705 | 2,632 | 7,200 | - | 27 | 23,102 |

**Case 21**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 2,175 | | | | | | | | | | | | 2,175 |
| **1** | | 3457 | 0.07 | 239 | 126 | 0.17 | 21 | 260 | 0 | 321 | 0 | 1.00 | 559 |
| **2** | | 3457 | 0.07 | 248 | 126 | 0.17 | 22 | 269 | 0 | 321 | 0 | 1.00 | 590 |
| **3** | | 3457 | 0.07 | 257 | 126 | 0.18 | 22 | 279 | 0 | 321 | 0 | 1.00 | 600 |
| **4** | | 3457 | 0.08 | 267 | 126 | 0.18 | 23 | 290 | 0 | 321 | 0 | 1.00 | 610 |
| **5** | | 3457 | 0.08 | 277 | 126 | 0.18 | 23 | 300 | 1120 | 321 | 0 | 1.00 | 1741 |
| **6** | | 3457 | 0.08 | 287 | 126 | 0.19 | 24 | 311 | 0 | 321 | 0 | 1.00 | 632 |
| **7** | | 3457 | 0.09 | 298 | 126 | 0.19 | 24 | 323 | 0 | 321 | 0 | 1.00 | 643 |
| **8** | | 3457 | 0.09 | 310 | 126 | 0.20 | 25 | 335 | 0 | 321 | 0 | 1.00 | 655 |
| **9** | | 3457 | 0.09 | 321 | 126 | 0.20 | 25 | 347 | 0 | 321 | 0 | 1.00 | 667 |
| **10** | | 3457 | 0.10 | 334 | 126 | 0.21 | 26 | 360 | 196 | 321 | 0 | 0.97 | 852 |
| **11** | | 3457 | 0.10 | 346 | 126 | 0.21 | 26 | 373 | 0 | 321 | 0 | 0.97 | 672 |
| **12** | | 3457 | 0.10 | 360 | 126 | 0.21 | 27 | 387 | 0 | 321 | 0 | 0.97 | 684 |
| **13** | | 3457 | 0.11 | 373 | 126 | 0.22 | 28 | 401 | 0 | 321 | 0 | 0.96 | 696 |
| **14** | | 3457 | 0.11 | 387 | 126 | 0.22 | 28 | 416 | 0 | 321 | 0 | 0.96 | 708 |
| **15** | | 3457 | 0.12 | 402 | 126 | 0.23 | 29 | 431 | 196 | 321 | 0 | 0.92 | 872 |
| **16** | | 3457 | 0.12 | 417 | 126 | 0.23 | 30 | 447 | 0 | 321 | 0 | 0.92 | 703 |
| **17** | | 3457 | 0.13 | 433 | 126 | 0.24 | 30 | 463 | 0 | 321 | 0 | 0.91 | 714 |
| **18** | | 3457 | 0.13 | 450 | 126 | 0.24 | 31 | 481 | 0 | 321 | 0 | 0.91 | 726 |
| **19** | | 3457 | 0.14 | 467 | 126 | 0.25 | 32 | 498 | 0 | 321 | 0 | 0.90 | 738 |
| **20** | | 3457 | 0.14 | 485 | 126 | 0.26 | 32 | 517 | 596 | 321 | 0 | 0.85 | 1212 |
| **21** | | 3457 | 0.15 | 503 | 126 | 0.26 | 33 | 536 | 0 | 321 | 0 | 0.84 | 718 |
| **22** | | 3457 | 0.15 | 522 | 126 | 0.27 | 34 | 556 | 0 | 321 | 0 | 0.83 | 729 |
| **23** | | 3457 | 0.16 | 542 | 126 | 0.27 | 34 | 576 | 0 | 321 | 0 | 0.82 | 740 |
| **24** | | 3457 | 0.16 | 563 | 126 | 0.28 | 35 | 598 | 0 | 321 | 0 | 0.82 | 751 |
| **25** | | 3457 | 0.17 | 584 | 126 | 0.28 | 36 | 620 | 1120 | 321 | 0 | 0.80 | 1647 |
| **26** | | 3457 | 0.18 | 606 | 126 | 0.29 | 37 | 643 | 0 | 321 | 0 | 0.79 | 763 |
| **27** | | 3457 | 0.18 | 629 | 126 | 0.30 | 38 | 667 | 0 | 321 | 0 | 0.79 | 775 |
| **28** | | 3457 | 0.19 | 653 | 126 | 0.30 | 38 | 691 | 0 | 321 | 0 | 0.78 | 787 |
| **29** | | 3457 | 0.20 | 678 | 126 | 0.31 | 39 | 717 | 0 | 321 | 0 | 0.77 | 800 |
| **30** | | 3457 | 0.20 | 704 | 126 | 0.32 | 40 | 744 | 0 | 321 | 80 | 0.76 | 752 |
| **Total** | 2,175 | 103,718 | 4 | 12,941 | 3,786 | 7 | 892 | 13,833 | 3,227 | 9,615 | 80 | 27 | 25,910 |

**Case 22**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,000 | | | | | | | | | | | | 4,000 |
| **1** | | 1706 | 0.07 | 118 | 128 | 0.17 | 22 | 139 | 0 | 290 | 0 | 1.00 | 429 |
| **2** | | 1706 | 0.07 | 122 | 128 | 0.17 | 22 | 144 | 0 | 290 | 0 | 1.00 | 434 |
| **3** | | 1706 | 0.07 | 127 | 128 | 0.18 | 23 | 149 | 0 | 290 | 0 | 1.00 | 439 |
| **4** | | 1706 | 0.08 | 132 | 128 | 0.18 | 23 | 155 | 0 | 290 | 0 | 1.00 | 445 |
| **5** | | 1706 | 0.08 | 137 | 128 | 0.18 | 24 | 160 | 1120 | 290 | 0 | 1.00 | 1570 |
| **6** | | 1706 | 0.08 | 142 | 128 | 0.19 | 24 | 166 | 0 | 290 | 0 | 1.00 | 456 |
| **7** | | 1706 | 0.09 | 147 | 128 | 0.19 | 25 | 172 | 0 | 290 | 0 | 1.00 | 462 |
| **8** | | 1706 | 0.09 | 153 | 128 | 0.20 | 25 | 178 | 0 | 290 | 0 | 1.00 | 468 |
| **9** | | 1706 | 0.09 | 159 | 128 | 0.20 | 26 | 184 | 0 | 290 | 0 | 1.00 | 474 |
| **10** | | 1706 | 0.10 | 165 | 128 | 0.21 | 26 | 191 | 196 | 290 | 0 | 0.97 | 658 |
| **11** | | 1706 | 0.10 | 171 | 128 | 0.21 | 27 | 198 | 0 | 290 | 0 | 0.97 | 473 |
| **12** | | 1706 | 0.10 | 177 | 128 | 0.21 | 27 | 205 | 0 | 290 | 0 | 0.97 | 478 |
| **13** | | 1706 | 0.11 | 184 | 128 | 0.22 | 28 | 212 | 0 | 290 | 0 | 0.96 | 484 |
| **14** | | 1706 | 0.11 | 191 | 128 | 0.22 | 29 | 220 | 0 | 290 | 0 | 0.96 | 490 |
| **15** | | 1706 | 0.12 | 198 | 128 | 0.23 | 29 | 228 | 196 | 290 | 0 | 0.92 | 657 |
| **16** | | 1706 | 0.12 | 206 | 128 | 0.23 | 30 | 236 | 0 | 290 | 0 | 0.92 | 482 |
| **17** | | 1706 | 0.13 | 214 | 128 | 0.24 | 31 | 244 | 0 | 290 | 0 | 0.91 | 487 |
| **18** | | 1706 | 0.13 | 222 | 128 | 0.24 | 31 | 253 | 0 | 290 | 0 | 0.91 | 492 |
| **19** | | 1706 | 0.14 | 230 | 128 | 0.25 | 32 | 262 | 0 | 290 | 0 | 0.90 | 498 |
| **20** | | 1706 | 0.14 | 239 | 128 | 0.26 | 33 | 272 | 3096 | 290 | 0 | 0.85 | 3093 |
| **21** | | 1706 | 0.15 | 248 | 128 | 0.26 | 33 | 281 | 0 | 290 | 0 | 0.84 | 479 |
| **22** | | 1706 | 0.15 | 258 | 128 | 0.27 | 34 | 292 | 0 | 290 | 0 | 0.83 | 484 |
| **23** | | 1706 | 0.16 | 267 | 128 | 0.27 | 35 | 302 | 0 | 290 | 0 | 0.82 | 488 |
| **24** | | 1706 | 0.16 | 277 | 128 | 0.28 | 36 | 313 | 0 | 290 | 0 | 0.82 | 493 |
| **25** | | 1706 | 0.17 | 288 | 128 | 0.28 | 36 | 324 | 1120 | 290 | 0 | 0.80 | 1386 |
| **26** | | 1706 | 0.18 | 299 | 128 | 0.29 | 37 | 336 | 0 | 290 | 0 | 0.79 | 496 |
| **27** | | 1706 | 0.18 | 310 | 128 | 0.30 | 38 | 348 | 0 | 290 | 0 | 0.79 | 501 |
| **28** | | 1706 | 0.19 | 322 | 128 | 0.30 | 39 | 361 | 0 | 290 | 0 | 0.78 | 506 |
| **29** | | 1706 | 0.20 | 334 | 128 | 0.31 | 40 | 374 | 0 | 290 | 0 | 0.77 | 512 |
| **30** | | 1706 | 0.20 | 347 | 128 | 0.32 | 41 | 388 | 0 | 290 | 1225 | 0.76 | -418 |
| **Total** | 4,000 | 51,166 | 4 | 6,384 | 3,828 | 7 | 902 | 7,286 | 5,727 | 8,700 | 1,225 | 27 | 22,396 |

**Case 23**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 7,444 | | | | | | | | | | | | 7,444 |
| **1** | | 1286 | 0.07 | 89 | 85 | 0.17 | 14 | 103 | 0 | 290 | 0 | 1.00 | 393 |
| **2** | | 1286 | 0.07 | 92 | 85 | 0.17 | 15 | 107 | 0 | 290 | 0 | 1.00 | 397 |
| **3** | | 1286 | 0.07 | 96 | 85 | 0.18 | 15 | 111 | 0 | 290 | 0 | 1.00 | 401 |
| **4** | | 1286 | 0.08 | 99 | 85 | 0.18 | 15 | 115 | 0 | 290 | 0 | 1.00 | 405 |
| **5** | | 1286 | 0.08 | 103 | 85 | 0.18 | 16 | 119 | 196 | 290 | 0 | 1.00 | 604 |
| **6** | | 1286 | 0.08 | 107 | 85 | 0.19 | 16 | 123 | 0 | 290 | 0 | 1.00 | 413 |
| **7** | | 1286 | 0.09 | 111 | 85 | 0.19 | 16 | 127 | 0 | 290 | 0 | 1.00 | 417 |
| **8** | | 1286 | 0.09 | 115 | 85 | 0.20 | 17 | 132 | 0 | 290 | 0 | 1.00 | 422 |
| **9** | | 1286 | 0.09 | 120 | 85 | 0.20 | 17 | 137 | 0 | 290 | 0 | 1.00 | 427 |
| **10** | | 1286 | 0.10 | 124 | 85 | 0.21 | 18 | 142 | 196 | 290 | 0 | 0.97 | 610 |
| **11** | | 1286 | 0.10 | 129 | 85 | 0.21 | 18 | 147 | 0 | 290 | 0 | 0.97 | 424 |
| **12** | | 1286 | 0.10 | 134 | 85 | 0.21 | 18 | 152 | 0 | 290 | 0 | 0.97 | 428 |
| **13** | | 1286 | 0.11 | 139 | 85 | 0.22 | 19 | 158 | 0 | 290 | 0 | 0.96 | 432 |
| **14** | | 1286 | 0.11 | 144 | 85 | 0.22 | 19 | 163 | 0 | 290 | 0 | 0.96 | 436 |
| **15** | | 1286 | 0.12 | 150 | 85 | 0.23 | 20 | 169 | 196 | 290 | 0 | 0.92 | 603 |
| **16** | | 1286 | 0.12 | 155 | 85 | 0.23 | 20 | 175 | 0 | 290 | 0 | 0.92 | 426 |
| **17** | | 1286 | 0.13 | 161 | 85 | 0.24 | 20 | 182 | 0 | 290 | 0 | 0.91 | 430 |
| **18** | | 1286 | 0.13 | 167 | 85 | 0.24 | 21 | 188 | 0 | 290 | 0 | 0.91 | 433 |
| **19** | | 1286 | 0.14 | 174 | 85 | 0.25 | 21 | 195 | 0 | 290 | 0 | 0.90 | 437 |
| **20** | | 1286 | 0.14 | 180 | 85 | 0.26 | 22 | 202 | 3096 | 290 | 0 | 0.85 | 3034 |
| **21** | | 1286 | 0.15 | 187 | 85 | 0.26 | 22 | 209 | 0 | 290 | 0 | 0.84 | 419 |
| **22** | | 1286 | 0.15 | 194 | 85 | 0.27 | 23 | 217 | 0 | 290 | 0 | 0.83 | 422 |
| **23** | | 1286 | 0.16 | 202 | 85 | 0.27 | 23 | 225 | 0 | 290 | 0 | 0.82 | 425 |
| **24** | | 1286 | 0.16 | 209 | 85 | 0.28 | 24 | 233 | 0 | 290 | 0 | 0.82 | 428 |
| **25** | | 1286 | 0.17 | 217 | 85 | 0 | 24 | 242 | 196 | 290 | 0 | 0.80 | 581 |
| **26** | | 1286 | 0.18 | 225 | 85 | 0 | 25 | 250 | 0 | 290 | 0 | 0.79 | 428 |
| **27** | | 1286 | 0.18 | 234 | 85 | 0 | 25 | 259 | 0 | 290 | 0 | 0.79 | 431 |
| **28** | | 1286 | 0.19 | 243 | 85 | 0 | 26 | 269 | 0 | 290 | 0 | 0.78 | 435 |
| **29** | | 1286 | 0.20 | 252 | 85 | 0 | 27 | 279 | 0 | 290 | 0 | 0.77 | 439 |
| **30** | | 1286 | 0.20 | 262 | 85 | 0 | 27 | 289 | 0 | 290 | 1375 | 0.76 | -608 |
| **Total** | 7,444 | 38,583 | 4 | 4,814 | 2,564 | 7 | 604 | 5,418 | 3,878 | 8,700 | 1,375 | 27 | 22,413 |

**Case 24**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 7,864 | | | | | | | | | | | | 7,864 |
| **1** | | 1267 | 0.07 | 87 | 84 | 0.17 | 14 | 102 | 0 | 330 | 0 | 1.00 | 432 |
| **2** | | 1267 | 0.07 | 91 | 84 | 0.17 | 14 | 105 | 0 | 330 | 0 | 1.00 | 435 |
| **3** | | 1267 | 0.07 | 94 | 84 | 0.18 | 15 | 109 | 0 | 330 | 0 | 1.00 | 439 |
| **4** | | 1267 | 0.08 | 98 | 84 | 0.18 | 15 | 113 | 0 | 330 | 0 | 1.00 | 443 |
| **5** | | 1267 | 0.08 | 102 | 84 | 0.18 | 15 | 117 | 196 | 330 | 0 | 1.00 | 643 |
| **6** | | 1267 | 0.08 | 105 | 84 | 0.19 | 16 | 121 | 0 | 330 | 0 | 1.00 | 451 |
| **7** | | 1267 | 0.09 | 109 | 84 | 0.19 | 16 | 125 | 0 | 330 | 0 | 1.00 | 455 |
| **8** | | 1267 | 0.09 | 114 | 84 | 0.20 | 16 | 130 | 0 | 330 | 0 | 1.00 | 460 |
| **9** | | 1267 | 0.09 | 118 | 84 | 0.20 | 17 | 135 | 0 | 330 | 0 | 1.00 | 465 |
| **10** | | 1267 | 0.10 | 122 | 84 | 0.21 | 17 | 140 | 196 | 330 | 0 | 0.97 | 647 |
| **11** | | 1267 | 0.10 | 127 | 84 | 0.21 | 18 | 145 | 0 | 330 | 0 | 0.97 | 460 |
| **12** | | 1267 | 0.10 | 132 | 84 | 0.21 | 18 | 150 | 0 | 330 | 0 | 0.97 | 464 |
| **13** | | 1267 | 0.11 | 137 | 84 | 0.22 | 18 | 155 | 0 | 330 | 0 | 0.96 | 468 |
| **14** | | 1267 | 0.11 | 142 | 84 | 0.22 | 19 | 161 | 0 | 330 | 0 | 0.96 | 472 |
| **15** | | 1267 | 0.12 | 147 | 84 | 0.23 | 19 | 167 | 196 | 330 | 0 | 0.92 | 637 |
| **16** | | 1267 | 0.12 | 153 | 84 | 0.23 | 20 | 173 | 0 | 330 | 0 | 0.92 | 460 |
| **17** | | 1267 | 0.13 | 159 | 84 | 0.24 | 20 | 179 | 0 | 330 | 0 | 0.91 | 464 |
| **18** | | 1267 | 0.13 | 165 | 84 | 0.24 | 20 | 185 | 0 | 330 | 0 | 0.91 | 467 |
| **19** | | 1267 | 0.14 | 171 | 84 | 0.25 | 21 | 192 | 0 | 330 | 0 | 0.90 | 470 |
| **20** | | 1267 | 0.14 | 178 | 84 | 0.26 | 21 | 199 | 3096 | 330 | 0 | 0.85 | 3065 |
| **21** | | 1267 | 0.15 | 184 | 84 | 0.26 | 22 | 206 | 0 | 330 | 0 | 0.84 | 450 |
| **22** | | 1267 | 0.15 | 191 | 84 | 0.27 | 22 | 214 | 0 | 330 | 0 | 0.83 | 452 |
| **23** | | 1267 | 0.16 | 199 | 84 | 0.27 | 23 | 221 | 0 | 330 | 0 | 0.82 | 455 |
| **24** | | 1267 | 0.16 | 206 | 84 | 0.28 | 23 | 229 | 0 | 330 | 0 | 0.82 | 458 |
| **25** | | 1267 | 0.17 | 214 | 84 | 0.28 | 24 | 238 | 196 | 330 | 0 | 0.80 | 610 |
| **26** | | 1267 | 0.18 | 222 | 84 | 0.29 | 24 | 246 | 0 | 330 | 0 | 0.79 | 457 |
| **27** | | 1267 | 0.18 | 231 | 84 | 0.30 | 25 | 255 | 0 | 330 | 0 | 0.79 | 460 |
| **28** | | 1267 | 0.19 | 239 | 84 | 0.30 | 25 | 265 | 0 | 330 | 0 | 0.78 | 463 |
| **29** | | 1267 | 0.20 | 248 | 84 | 0.31 | 26 | 274 | 0 | 330 | 0 | 0.77 | 466 |
| **30** | | 1267 | 0.20 | 258 | 84 | 0.32 | 27 | 284 | 0 | 330 | 1375 | 0.76 | -581 |
| **Total** | 7,864 | 38,015 | 4 | 4,743 | 2,511 | 7 | 592 | 5,335 | 3,878 | 9,900 | 1,375 | 27 | 23,849 |

| Case 25 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| 0 | 8,444 | | | | | | | | | | | | 8,444 |
| 1 | | 1273 | 0.07 | 88 | 75 | 0.17 | 13 | 100 | 0 | 330 | 0 | 1.00 | 430 |
| 2 | | 1273 | 0.07 | 91 | 75 | 0.17 | 13 | 104 | 0 | 330 | 0 | 1.00 | 434 |
| 3 | | 1273 | 0.07 | 95 | 75 | 0.18 | 13 | 108 | 0 | 330 | 0 | 1.00 | 438 |
| 4 | | 1273 | 0.08 | 98 | 75 | 0.18 | 13 | 112 | 0 | 330 | 0 | 1.00 | 442 |
| 5 | | 1273 | 0.08 | 102 | 75 | 0.18 | 14 | 116 | 196 | 330 | 0 | 1.00 | 641 |
| 6 | | 1273 | 0.08 | 106 | 75 | 0.19 | 14 | 120 | 0 | 330 | 0 | 1.00 | 450 |
| 7 | | 1273 | 0.09 | 110 | 75 | 0.19 | 14 | 124 | 0 | 330 | 0 | 1.00 | 454 |
| 8 | | 1273 | 0.09 | 114 | 75 | 0.20 | 15 | 129 | 0 | 330 | 0 | 1.00 | 459 |
| 9 | | 1273 | 0.09 | 118 | 75 | 0.20 | 15 | 133 | 0 | 330 | 0 | 1.00 | 463 |
| 10 | | 1273 | 0.10 | 123 | 75 | 0.21 | 15 | 138 | 196 | 330 | 0 | 0.97 | 646 |
| 11 | | 1273 | 0.10 | 128 | 75 | 0.21 | 16 | 143 | 0 | 330 | 0 | 0.97 | 459 |
| 12 | | 1273 | 0.10 | 132 | 75 | 0.21 | 16 | 148 | 0 | 330 | 0 | 0.97 | 463 |
| 13 | | 1273 | 0.11 | 137 | 75 | 0.22 | 16 | 154 | 0 | 330 | 0 | 0.96 | 467 |
| 14 | | 1273 | 0.11 | 143 | 75 | 0.22 | 17 | 159 | 0 | 330 | 0 | 0.96 | 471 |
| 15 | | 1273 | 0.12 | 148 | 75 | 0.23 | 17 | 165 | 196 | 330 | 0 | 0.92 | 636 |
| 16 | | 1273 | 0.12 | 154 | 75 | 0.23 | 17 | 171 | 0 | 330 | 0 | 0.92 | 459 |
| 17 | | 1273 | 0.13 | 160 | 75 | 0.24 | 18 | 177 | 0 | 330 | 0 | 0.91 | 462 |
| 18 | | 1273 | 0.13 | 166 | 75 | 0.24 | 18 | 184 | 0 | 330 | 0 | 0.91 | 466 |
| 19 | | 1273 | 0.14 | 172 | 75 | 0.25 | 19 | 191 | 0 | 330 | 0 | 0.90 | 469 |
| 20 | | 1273 | 0.14 | 178 | 75 | 0.26 | 19 | 197 | 4096 | 330 | 0 | 0.85 | 3909 |
| 21 | | 1273 | 0.15 | 185 | 75 | 0.26 | 19 | 205 | 0 | 330 | 0 | 0.84 | 448 |
| 22 | | 1273 | 0.15 | 192 | 75 | 0.27 | 20 | 212 | 0 | 330 | 0 | 0.83 | 451 |
| 23 | | 1273 | 0.16 | 200 | 75 | 0.27 | 20 | 220 | 0 | 330 | 0 | 0.82 | 453 |
| 24 | | 1273 | 0.16 | 207 | 75 | 0.28 | 21 | 228 | 0 | 330 | 0 | 0.82 | 456 |
| 25 | | 1273 | 0.17 | 215 | 75 | 0.28 | 21 | 236 | 196 | 330 | 0 | 0.80 | 609 |
| 26 | | 1273 | 0.18 | 223 | 75 | 0.29 | 22 | 245 | 0 | 330 | 0 | 0.79 | 455 |
| 27 | | 1273 | 0.18 | 232 | 75 | 0.30 | 22 | 254 | 0 | 330 | 0 | 0.79 | 458 |
| 28 | | 1273 | 0.19 | 240 | 75 | 0.30 | 23 | 263 | 0 | 330 | 0 | 0.78 | 462 |
| 29 | | 1273 | 0.20 | 250 | 75 | 0.31 | 23 | 273 | 0 | 330 | 0 | 0.77 | 465 |
| 30 | | 1273 | 0.20 | 259 | 75 | 0.32 | 24 | 283 | 0 | 330 | 1620 | 0.76 | -770 |
| Total | 8,444 | 38,195 | 4 | 4,766 | 2,239 | 7 | 528 | 5,293 | 4,878 | 9,900 | 1,620 | 27 | 25,050 |

| Case 26 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| 0 | 8,864 | | | | | | | | | | | | 8,864 |
| 1 | | 1254 | 0.07 | 87 | 73 | 0.17 | 12 | 99 | 0 | 330 | 0 | 1.00 | 429 |
| 2 | | 1254 | 0.07 | 90 | 73 | 0.17 | 13 | 102 | 0 | 330 | 0 | 1.00 | 432 |
| 3 | | 1254 | 0.07 | 93 | 73 | 0.18 | 13 | 106 | 0 | 330 | 0 | 1.00 | 436 |
| 4 | | 1254 | 0.08 | 97 | 73 | 0.18 | 13 | 110 | 0 | 330 | 0 | 1.00 | 440 |
| 5 | | 1254 | 0.08 | 100 | 73 | 0.18 | 13 | 114 | 196 | 330 | 0 | 1.00 | 640 |
| 6 | | 1254 | 0.08 | 104 | 73 | 0.19 | 14 | 118 | 0 | 330 | 0 | 1.00 | 448 |
| 7 | | 1254 | 0.09 | 108 | 73 | 0.19 | 14 | 122 | 0 | 330 | 0 | 1.00 | 452 |
| 8 | | 1254 | 0.09 | 112 | 73 | 0.20 | 14 | 127 | 0 | 330 | 0 | 1.00 | 457 |
| 9 | | 1254 | 0.09 | 117 | 73 | 0.20 | 15 | 131 | 0 | 330 | 0 | 1.00 | 461 |
| 10 | | 1254 | 0.10 | 121 | 73 | 0.21 | 15 | 136 | 196 | 330 | 0 | 0.97 | 643 |
| 11 | | 1254 | 0.10 | 126 | 73 | 0.21 | 15 | 141 | 0 | 330 | 0 | 0.97 | 457 |
| 12 | | 1254 | 0.10 | 130 | 73 | 0.21 | 16 | 146 | 0 | 330 | 0 | 0.97 | 460 |
| 13 | | 1254 | 0.11 | 135 | 73 | 0.22 | 16 | 151 | 0 | 330 | 0 | 0.96 | 464 |
| 14 | | 1254 | 0.11 | 141 | 73 | 0.22 | 16 | 157 | 0 | 330 | 0 | 0.96 | 468 |
| 15 | | 1254 | 0.12 | 146 | 73 | 0.23 | 17 | 163 | 196 | 330 | 0 | 0.92 | 634 |
| 16 | | 1254 | 0.12 | 151 | 73 | 0.23 | 17 | 169 | 0 | 330 | 0 | 0.92 | 457 |
| 17 | | 1254 | 0.13 | 157 | 73 | 0.24 | 17 | 175 | 0 | 330 | 0 | 0.91 | 460 |
| 18 | | 1254 | 0.13 | 163 | 73 | 0.24 | 18 | 181 | 0 | 330 | 0 | 0.91 | 463 |
| 19 | | 1254 | 0.14 | 169 | 73 | 0.25 | 18 | 188 | 0 | 330 | 0 | 0.90 | 466 |
| 20 | | 1254 | 0.14 | 176 | 73 | 0.26 | 19 | 194 | 4096 | 330 | 0 | 0.85 | 3907 |
| 21 | | 1254 | 0.15 | 182 | 73 | 0.26 | 19 | 202 | 0 | 330 | 0 | 0.84 | 446 |
| 22 | | 1254 | 0.15 | 189 | 73 | 0.27 | 20 | 209 | 0 | 330 | 0 | 0.83 | 448 |
| 23 | | 1254 | 0.16 | 197 | 73 | 0.27 | 20 | 217 | 0 | 330 | 0 | 0.82 | 451 |
| 24 | | 1254 | 0.16 | 204 | 73 | 0.28 | 20 | 224 | 0 | 330 | 0 | 0.82 | 453 |
| 25 | | 1254 | 0.17 | 212 | 73 | 0.28 | 21 | 233 | 196 | 330 | 0 | 0.80 | 606 |
| 26 | | 1254 | 0.18 | 220 | 73 | 0.29 | 21 | 241 | 0 | 330 | 0 | 0.79 | 452 |
| 27 | | 1254 | 0.18 | 228 | 73 | 0.30 | 22 | 250 | 0 | 330 | 0 | 0.79 | 455 |
| 28 | | 1254 | 0.19 | 237 | 73 | 0.30 | 22 | 259 | 0 | 330 | 0 | 0.78 | 458 |
| 29 | | 1254 | 0.20 | 246 | 73 | 0.31 | 23 | 269 | 0 | 330 | 0 | 0.77 | 462 |
| 30 | | 1254 | 0.20 | 255 | 73 | 0.32 | 23 | 278 | 0 | 330 | 1620 | 0.76 | -773 |
| Total | 8,864 | 37,634 | 4 | 4,696 | 2,193 | 7 | 517 | 5,212 | 4,878 | 9,900 | 1,620 | 27 | 25,398 |

**Case 27**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 8,965 | | | | | | | | | | | | 8,965 |
| **1** | | 1005 | 0.07 | 69 | 86 | 0.17 | 14 | 84 | 0 | 330 | 0 | 1.00 | 414 |
| **2** | | 1005 | 0.07 | 72 | 86 | 0.17 | 15 | 87 | 0 | 330 | 0 | 1.00 | 417 |
| **3** | | 1005 | 0.07 | 75 | 86 | 0.18 | 15 | 90 | 0 | 330 | 0 | 1.00 | 420 |
| **4** | | 1005 | 0.08 | 78 | 86 | 0.18 | 15 | 93 | 0 | 330 | 0 | 1.00 | 423 |
| **5** | | 1005 | 0.08 | 80 | 86 | 0.18 | 16 | 96 | 0 | 330 | 0 | 1.00 | 426 |
| **6** | | 1005 | 0.08 | 84 | 86 | 0.19 | 16 | 100 | 0 | 330 | 0 | 1.00 | 430 |
| **7** | | 1005 | 0.09 | 87 | 86 | 0.19 | 16 | 103 | 0 | 330 | 0 | 1.00 | 433 |
| **8** | | 1005 | 0.09 | 90 | 86 | 0.20 | 17 | 107 | 0 | 330 | 0 | 1.00 | 437 |
| **9** | | 1005 | 0.09 | 93 | 86 | 0.20 | 17 | 111 | 0 | 330 | 0 | 1.00 | 441 |
| **10** | | 1005 | 0.10 | 97 | 86 | 0.21 | 18 | 115 | 0 | 330 | 0 | 0.97 | 432 |
| **11** | | 1005 | 0.10 | 101 | 86 | 0.21 | 18 | 119 | 0 | 330 | 0 | 0.97 | 435 |
| **12** | | 1005 | 0.10 | 104 | 86 | 0.21 | 18 | 123 | 0 | 330 | 0 | 0.97 | 438 |
| **13** | | 1005 | 0.11 | 108 | 86 | 0.22 | 19 | 127 | 0 | 330 | 0 | 0.96 | 441 |
| **14** | | 1005 | 0.11 | 113 | 86 | 0.22 | 19 | 132 | 0 | 330 | 0 | 0.96 | 444 |
| **15** | | 1005 | 0.12 | 117 | 86 | 0.23 | 20 | 136 | 196 | 330 | 0 | 0.92 | 610 |
| **16** | | 1005 | 0.12 | 121 | 86 | 0.23 | 20 | 141 | 0 | 330 | 0 | 0.92 | 432 |
| **17** | | 1005 | 0.13 | 126 | 86 | 0.24 | 21 | 146 | 0 | 330 | 0 | 0.91 | 434 |
| **18** | | 1005 | 0.13 | 131 | 86 | 0.24 | 21 | 152 | 0 | 330 | 0 | 0.91 | 436 |
| **19** | | 1005 | 0.14 | 136 | 86 | 0.25 | 21 | 157 | 0 | 330 | 0 | 0.90 | 439 |
| **20** | | 1005 | 0.14 | 141 | 86 | 0.26 | 22 | 163 | 2900 | 330 | 0 | 0.85 | 2869 |
| **21** | | 1005 | 0.15 | 146 | 86 | 0.26 | 22 | 169 | 0 | 330 | 0 | 0.84 | 418 |
| **22** | | 1005 | 0.15 | 152 | 86 | 0.27 | 23 | 175 | 0 | 330 | 0 | 0.83 | 420 |
| **23** | | 1005 | 0.16 | 157 | 86 | 0.27 | 23 | 181 | 0 | 330 | 0 | 0.82 | 421 |
| **24** | | 1005 | 0.16 | 163 | 86 | 0.28 | 24 | 187 | 0 | 330 | 0 | 0.82 | 423 |
| **25** | | 1005 | 0.17 | 170 | 86 | 0.28 | 24 | 194 | 0 | 330 | 0 | 0.80 | 419 |
| **26** | | 1005 | 0.18 | 176 | 86 | 0.29 | 25 | 201 | 0 | 330 | 0 | 0.79 | 421 |
| **27** | | 1005 | 0.18 | 183 | 86 | 0.30 | 25 | 208 | 0 | 330 | 0 | 0.79 | 423 |
| **28** | | 1005 | 0.19 | 190 | 86 | 0.30 | 26 | 216 | 0 | 330 | 0 | 0.78 | 425 |
| **29** | | 1005 | 0.20 | 197 | 86 | 0.31 | 27 | 224 | 0 | 330 | 0 | 0.77 | 427 |
| **30** | | 1005 | 0.20 | 204 | 86 | 0.32 | 27 | 232 | 0 | 330 | 1375 | 0.76 | -622 |
| **Total** | 8,965 | 30,137 | 4 | 3,760 | 2,571 | 7 | 606 | 4,366 | 3,096 | 9,900 | 1,375 | 27 | 23,389 |

**Case 28**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 9,385 | | | | | | | | | | | | 9,385 |
| **1** | | 981 | 0.07 | 68 | 84 | 0.17 | 14 | 82 | 0 | 330 | 0 | 1.00 | 412 |
| **2** | | 981 | 0.07 | 70 | 84 | 0.17 | 14 | 85 | 0 | 330 | 0 | 1.00 | 415 |
| **3** | | 981 | 0.07 | 73 | 84 | 0.18 | 15 | 88 | 0 | 330 | 0 | 1.00 | 418 |
| **4** | | 981 | 0.08 | 76 | 84 | 0.18 | 15 | 91 | 0 | 330 | 0 | 1.00 | 421 |
| **5** | | 981 | 0.08 | 79 | 84 | 0.18 | 15 | 94 | 0 | 330 | 0 | 1.00 | 424 |
| **6** | | 981 | 0.08 | 82 | 84 | 0.19 | 16 | 97 | 0 | 330 | 0 | 1.00 | 427 |
| **7** | | 981 | 0.09 | 85 | 84 | 0.19 | 16 | 101 | 0 | 330 | 0 | 1.00 | 431 |
| **8** | | 981 | 0.09 | 88 | 84 | 0.20 | 16 | 104 | 0 | 330 | 0 | 1.00 | 434 |
| **9** | | 981 | 0.09 | 91 | 84 | 0.20 | 17 | 108 | 0 | 330 | 0 | 1.00 | 438 |
| **10** | | 981 | 0.10 | 95 | 84 | 0.21 | 17 | 112 | 0 | 330 | 0 | 0.97 | 430 |
| **11** | | 981 | 0.10 | 98 | 84 | 0.21 | 18 | 116 | 0 | 330 | 0 | 0.97 | 432 |
| **12** | | 981 | 0.10 | 102 | 84 | 0.21 | 18 | 120 | 0 | 330 | 0 | 0.97 | 435 |
| **13** | | 981 | 0.11 | 106 | 84 | 0.22 | 18 | 124 | 0 | 330 | 0 | 0.96 | 438 |
| **14** | | 981 | 0.11 | 110 | 84 | 0.22 | 19 | 129 | 0 | 330 | 0 | 0.96 | 441 |
| **15** | | 981 | 0.12 | 114 | 84 | 0.23 | 19 | 133 | 196 | 330 | 0 | 0.92 | 607 |
| **16** | | 981 | 0.12 | 118 | 84 | 0.23 | 20 | 138 | 0 | 330 | 0 | 0.92 | 429 |
| **17** | | 981 | 0.13 | 123 | 84 | 0.24 | 20 | 143 | 0 | 330 | 0 | 0.91 | 431 |
| **18** | | 981 | 0.13 | 128 | 84 | 0.24 | 20 | 148 | 0 | 330 | 0 | 0.91 | 433 |
| **19** | | 981 | 0.14 | 132 | 84 | 0.25 | 21 | 153 | 0 | 330 | 0 | 0.90 | 436 |
| **20** | | 981 | 0.14 | 138 | 84 | 0.26 | 21 | 159 | 2900 | 330 | 0 | 0.85 | 2866 |
| **21** | | 981 | 0.15 | 143 | 84 | 0.26 | 22 | 165 | 0 | 330 | 0 | 0.84 | 415 |
| **22** | | 981 | 0.15 | 148 | 84 | 0.27 | 22 | 170 | 0 | 330 | 0 | 0.83 | 416 |
| **23** | | 981 | 0.16 | 154 | 84 | 0.27 | 23 | 177 | 0 | 330 | 0 | 0.82 | 418 |
| **24** | | 981 | 0.16 | 160 | 84 | 0.28 | 23 | 183 | 0 | 330 | 0 | 0.82 | 419 |
| **25** | | 981 | 0.17 | 166 | 84 | 0.28 | 24 | 190 | 0 | 330 | 0 | 0.80 | 415 |
| **26** | | 981 | 0.18 | 172 | 84 | 0.29 | 24 | 196 | 0 | 330 | 0 | 0.79 | 417 |
| **27** | | 981 | 0.18 | 179 | 84 | 0.30 | 25 | 203 | 0 | 330 | 0 | 0.79 | 419 |
| **28** | | 981 | 0.19 | 185 | 84 | 0.30 | 25 | 211 | 0 | 330 | 0 | 0.78 | 421 |
| **29** | | 981 | 0.20 | 192 | 84 | 0.31 | 26 | 218 | 0 | 330 | 0 | 0.77 | 423 |
| **30** | | 981 | 0.20 | 200 | 84 | 0.32 | 27 | 226 | 0 | 330 | 1375 | 0.76 | -626 |
| **Total** | 9,385 | 29,439 | 4 | 3,673 | 2,509 | 7 | 591 | 4,265 | 3,096 | 9,900 | 1,375 | 27 | 23,719 |

| Case 29 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 9,063 | | | | | | | | | | | | 9,063 |
| **1** | | 991 | 0.07 | 68 | 86 | 0.17 | 14 | 83 | 0 | 290 | 0 | 1.00 | 373 |
| **2** | | 991 | 0.07 | 71 | 86 | 0.17 | 15 | 86 | 0 | 290 | 0 | 1.00 | 376 |
| **3** | | 991 | 0.07 | 74 | 86 | 0.18 | 15 | 89 | 0 | 290 | 0 | 1.00 | 379 |
| **4** | | 991 | 0.08 | 76 | 86 | 0.18 | 15 | 92 | 0 | 290 | 0 | 1.00 | 382 |
| **5** | | 991 | 0.08 | 79 | 86 | 0.18 | 16 | 95 | 0 | 290 | 0 | 1.00 | 385 |
| **6** | | 991 | 0.08 | 82 | 86 | 0.19 | 16 | 99 | 0 | 290 | 0 | 1.00 | 389 |
| **7** | | 991 | 0.09 | 86 | 86 | 0.19 | 16 | 102 | 0 | 290 | 0 | 1.00 | 392 |
| **8** | | 991 | 0.09 | 89 | 86 | 0.20 | 17 | 106 | 0 | 290 | 0 | 1.00 | 396 |
| **9** | | 991 | 0.09 | 92 | 86 | 0.20 | 17 | 109 | 0 | 290 | 0 | 1.00 | 399 |
| **10** | | 991 | 0.10 | 96 | 86 | 0.21 | 18 | 113 | 0 | 290 | 0 | 0.97 | 392 |
| **11** | | 991 | 0.10 | 99 | 86 | 0.21 | 18 | 117 | 0 | 290 | 0 | 0.97 | 395 |
| **12** | | 991 | 0.10 | 103 | 86 | 0.21 | 18 | 121 | 0 | 290 | 0 | 0.97 | 398 |
| **13** | | 991 | 0.11 | 107 | 86 | 0.22 | 19 | 126 | 0 | 290 | 0 | 0.96 | 401 |
| **14** | | 991 | 0.11 | 111 | 86 | 0.22 | 19 | 130 | 0 | 290 | 0 | 0.96 | 404 |
| **15** | | 991 | 0.12 | 115 | 86 | 0.23 | 20 | 135 | 196 | 290 | 0 | 0.92 | 571 |
| **16** | | 991 | 0.12 | 120 | 86 | 0.23 | 20 | 140 | 0 | 290 | 0 | 0.92 | 394 |
| **17** | | 991 | 0.13 | 124 | 86 | 0.24 | 20 | 145 | 0 | 290 | 0 | 0.91 | 396 |
| **18** | | 991 | 0.13 | 129 | 86 | 0.24 | 21 | 150 | 0 | 290 | 0 | 0.91 | 399 |
| **19** | | 991 | 0.14 | 134 | 86 | 0.25 | 21 | 155 | 0 | 290 | 0 | 0.90 | 401 |
| **20** | | 991 | 0.14 | 139 | 86 | 0.26 | 22 | 161 | 2900 | 290 | 0 | 0.85 | 2833 |
| **21** | | 991 | 0.15 | 144 | 86 | 0.26 | 22 | 167 | 0 | 290 | 0 | 0.84 | 383 |
| **22** | | 991 | 0.15 | 150 | 86 | 0.27 | 23 | 173 | 0 | 290 | 0 | 0.83 | 385 |
| **23** | | 991 | 0.16 | 155 | 86 | 0.27 | 23 | 179 | 0 | 290 | 0 | 0.82 | 386 |
| **24** | | 991 | 0.16 | 161 | 86 | 0.28 | 24 | 185 | 0 | 290 | 0 | 0.82 | 389 |
| **25** | | 991 | 0.17 | 167 | 86 | 0.28 | 24 | 192 | 0 | 290 | 0 | 0.80 | 385 |
| **26** | | 991 | 0.18 | 174 | 86 | 0.29 | 25 | 199 | 0 | 290 | 0 | 0.79 | 387 |
| **27** | | 991 | 0.18 | 180 | 86 | 0.30 | 25 | 206 | 0 | 290 | 0 | 0.79 | 389 |
| **28** | | 991 | 0.19 | 187 | 86 | 0.30 | 26 | 213 | 0 | 290 | 0 | 0.78 | 392 |
| **29** | | 991 | 0.20 | 194 | 86 | 0.31 | 27 | 221 | 0 | 290 | 0 | 0.77 | 394 |
| **30** | | 991 | 0.20 | 202 | 86 | 0.32 | 27 | 229 | 0 | 290 | 1375 | 0.76 | -654 |
| **Total** | 9,063 | 29,733 | 4 | 3,710 | 2,569 | 7 | 605 | 4,315 | 3,096 | 8,700 | 1,375 | 27 | 22,352 |

| Case 30 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 9,483 | | | | | | | | | | | | 9,483 |
| **1** | | 967 | 0.07 | 67 | 84 | 0.17 | 14 | 81 | 0 | 290 | 0 | 1.00 | 371 |
| **2** | | 967 | 0.07 | 69 | 84 | 0.17 | 14 | 84 | 0 | 290 | 0 | 1.00 | 374 |
| **3** | | 967 | 0.07 | 72 | 84 | 0.18 | 15 | 87 | 0 | 290 | 0 | 1.00 | 377 |
| **4** | | 967 | 0.08 | 75 | 84 | 0.18 | 15 | 90 | 0 | 290 | 0 | 1.00 | 380 |
| **5** | | 967 | 0.08 | 77 | 84 | 0.18 | 15 | 93 | 0 | 290 | 0 | 1.00 | 383 |
| **6** | | 967 | 0.08 | 80 | 84 | 0.19 | 16 | 96 | 0 | 290 | 0 | 1.00 | 386 |
| **7** | | 967 | 0.09 | 83 | 84 | 0.19 | 16 | 100 | 0 | 290 | 0 | 1.00 | 390 |
| **8** | | 967 | 0.09 | 87 | 84 | 0.20 | 16 | 103 | 0 | 290 | 0 | 1.00 | 393 |
| **9** | | 967 | 0.09 | 90 | 84 | 0.20 | 17 | 107 | 0 | 290 | 0 | 1.00 | 397 |
| **10** | | 967 | 0.10 | 93 | 84 | 0.21 | 17 | 111 | 0 | 290 | 0 | 0.97 | 389 |
| **11** | | 967 | 0.10 | 97 | 84 | 0.21 | 18 | 114 | 0 | 290 | 0 | 0.97 | 392 |
| **12** | | 967 | 0.10 | 101 | 84 | 0.21 | 18 | 119 | 0 | 290 | 0 | 0.97 | 395 |
| **13** | | 967 | 0.11 | 104 | 84 | 0.22 | 18 | 123 | 0 | 290 | 0 | 0.96 | 398 |
| **14** | | 967 | 0.11 | 108 | 84 | 0.22 | 19 | 127 | 0 | 290 | 0 | 0.96 | 401 |
| **15** | | 967 | 0.12 | 113 | 84 | 0.23 | 19 | 132 | 196 | 290 | 0 | 0.92 | 568 |
| **16** | | 967 | 0.12 | 117 | 84 | 0.23 | 20 | 136 | 0 | 290 | 0 | 0.92 | 391 |
| **17** | | 967 | 0.13 | 121 | 84 | 0.24 | 20 | 141 | 0 | 290 | 0 | 0.91 | 393 |
| **18** | | 967 | 0.13 | 126 | 84 | 0.24 | 20 | 146 | 0 | 290 | 0 | 0.91 | 395 |
| **19** | | 967 | 0.14 | 131 | 84 | 0.25 | 21 | 151 | 0 | 290 | 0 | 0.90 | 398 |
| **20** | | 967 | 0.14 | 136 | 84 | 0.26 | 21 | 157 | 2900 | 290 | 0 | 0.85 | 2830 |
| **21** | | 967 | 0.15 | 141 | 84 | 0.26 | 22 | 163 | 0 | 290 | 0 | 0.84 | 379 |
| **22** | | 967 | 0.15 | 146 | 84 | 0.27 | 22 | 168 | 0 | 290 | 0 | 0.83 | 381 |
| **23** | | 967 | 0.16 | 152 | 84 | 0.27 | 23 | 174 | 0 | 290 | 0 | 0.82 | 383 |
| **24** | | 967 | 0.16 | 157 | 84 | 0.28 | 23 | 181 | 0 | 290 | 0 | 0.82 | 385 |
| **25** | | 967 | 0.17 | 163 | 84 | 0.28 | 24 | 187 | 0 | 290 | 0 | 0.80 | 381 |
| **26** | | 967 | 0.18 | 170 | 84 | 0.29 | 24 | 194 | 0 | 290 | 0 | 0.79 | 383 |
| **27** | | 967 | 0.18 | 176 | 84 | 0.30 | 25 | 201 | 0 | 290 | 0 | 0.79 | 385 |
| **28** | | 967 | 0.19 | 183 | 84 | 0.30 | 25 | 208 | 0 | 290 | 0 | 0.78 | 388 |
| **29** | | 967 | 0.20 | 190 | 84 | 0.31 | 26 | 216 | 0 | 290 | 0 | 0.77 | 390 |
| **30** | | 967 | 0 | 197 | 84 | 0.32 | 27 | 223 | 0 | 290 | 1375 | 0.76 | -659 |
| **Total** | 9,483 | 29,022 | 4 | 3,621 | 2,506 | 7 | 591 | 4,212 | 3,096 | 8,700 | 1,375 | 27 | 22,681 |

**Case 31**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 10,063 | | | | | | | | | | | | 10,063 |
| **1** | | 978 | 0.07 | 68 | 74 | 0.17 | 13 | 80 | 0 | 330 | 0 | 1.00 | 410 |
| **2** | | 978 | 0.07 | 70 | 74 | 0.17 | 13 | 83 | 0 | 330 | 0 | 1.00 | 413 |
| **3** | | 978 | 0.07 | 73 | 74 | 0.18 | 13 | 86 | 0 | 330 | 0 | 1.00 | 416 |
| **4** | | 978 | 0.08 | 76 | 74 | 0.18 | 13 | 89 | 0 | 330 | 0 | 1.00 | 419 |
| **5** | | 978 | 0.08 | 78 | 74 | 0.18 | 14 | 92 | 0 | 330 | 0 | 0.99 | 416 |
| **6** | | 978 | 0.08 | 81 | 74 | 0.19 | 14 | 95 | 0 | 330 | 0 | 0.98 | 418 |
| **7** | | 978 | 0.09 | 84 | 74 | 0.19 | 14 | 99 | 0 | 330 | 0 | 0.98 | 420 |
| **8** | | 978 | 0.09 | 88 | 74 | 0.20 | 15 | 102 | 0 | 330 | 0 | 0.98 | 423 |
| **9** | | 978 | 0.09 | 91 | 74 | 0.20 | 15 | 106 | 0 | 330 | 0 | 0.98 | 425 |
| **10** | | 978 | 0.10 | 94 | 74 | 0.21 | 15 | 110 | 0 | 330 | 0 | 0.95 | 416 |
| **11** | | 978 | 0.10 | 98 | 74 | 0.21 | 16 | 114 | 0 | 330 | 0 | 0.94 | 418 |
| **12** | | 978 | 0.10 | 102 | 74 | 0.21 | 16 | 118 | 0 | 330 | 0 | 0.94 | 419 |
| **13** | | 978 | 0.11 | 106 | 74 | 0.22 | 16 | 122 | 0 | 330 | 0 | 0.93 | 421 |
| **14** | | 978 | 0.11 | 110 | 74 | 0.22 | 17 | 126 | 0 | 330 | 0 | 0.93 | 423 |
| **15** | | 978 | 0.12 | 114 | 74 | 0.23 | 17 | 131 | 196 | 330 | 0 | 0.92 | 605 |
| **16** | | 978 | 0.12 | 118 | 74 | 0.23 | 17 | 136 | 0 | 330 | 0 | 0.92 | 426 |
| **17** | | 978 | 0.13 | 123 | 74 | 0.24 | 18 | 140 | 0 | 330 | 0 | 0.91 | 429 |
| **18** | | 978 | 0.13 | 127 | 74 | 0.24 | 18 | 145 | 0 | 330 | 0 | 0.91 | 431 |
| **19** | | 978 | 0.14 | 132 | 74 | 0.25 | 19 | 151 | 0 | 330 | 0 | 0.90 | 433 |
| **20** | | 978 | 0.14 | 137 | 74 | 0.26 | 19 | 156 | 3900 | 330 | 0 | 0.85 | 3709 |
| **21** | | 978 | 0.15 | 142 | 74 | 0.26 | 19 | 162 | 0 | 330 | 0 | 0.84 | 412 |
| **22** | | 978 | 0.15 | 148 | 74 | 0.27 | 20 | 168 | 0 | 330 | 0 | 0.83 | 414 |
| **23** | | 978 | 0.16 | 153 | 74 | 0.27 | 20 | 174 | 0 | 330 | 0 | 0.82 | 415 |
| **24** | | 978 | 0.16 | 159 | 74 | 0.28 | 21 | 180 | 0 | 330 | 0 | 0.82 | 417 |
| **25** | | 978 | 0.17 | 165 | 74 | 0.28 | 21 | 186 | 0 | 330 | 0 | 0.93 | 482 |
| **26** | | 978 | 0.18 | 172 | 74 | 0.29 | 22 | 193 | 0 | 330 | 0 | 0.76 | 396 |
| **27** | | 978 | 0.18 | 178 | 74 | 0.30 | 22 | 200 | 0 | 330 | 0 | 0.75 | 397 |
| **28** | | 978 | 0.19 | 185 | 74 | 0.30 | 23 | 207 | 0 | 330 | 0 | 0.74 | 398 |
| **29** | | 978 | 0.20 | 192 | 74 | 0.31 | 23 | 215 | 0 | 330 | 0 | 0.73 | 399 |
| **30** | | 978 | 0.20 | 199 | 74 | 0.32 | 24 | 223 | 0 | 330 | 1620 | 0.72 | -773 |
| **Total** | 10,063 | 29,354 | 4 | 3,663 | 2,229 | 7 | 525 | 4,188 | 4,096 | 9,900 | 1,620 | 27 | 24,908 |

**Case 32**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 10,483 | | | | | | | | | | | | 10,483 |
| **1** | | 955 | 0.07 | 66 | 73 | 0.17 | 12 | 78 | 0 | 330 | 0 | 1.00 | 408 |
| **2** | | 955 | 0.07 | 68 | 73 | 0.17 | 13 | 81 | 0 | 330 | 0 | 1.00 | 411 |
| **3** | | 955 | 0.07 | 71 | 73 | 0.18 | 13 | 84 | 0 | 330 | 0 | 1.00 | 414 |
| **4** | | 955 | 0.08 | 74 | 73 | 0.18 | 13 | 87 | 0 | 330 | 0 | 1.00 | 417 |
| **5** | | 955 | 0.08 | 76 | 73 | 0.18 | 13 | 90 | 0 | 330 | 0 | 1.00 | 420 |
| **6** | | 955 | 0.08 | 79 | 73 | 0.19 | 14 | 93 | 0 | 330 | 0 | 1.00 | 423 |
| **7** | | 955 | 0.09 | 82 | 73 | 0.19 | 14 | 96 | 0 | 330 | 0 | 1.00 | 426 |
| **8** | | 955 | 0.09 | 86 | 73 | 0.20 | 14 | 100 | 0 | 330 | 0 | 1.00 | 430 |
| **9** | | 955 | 0.09 | 89 | 73 | 0.20 | 15 | 103 | 0 | 330 | 0 | 1.00 | 433 |
| **10** | | 955 | 0.10 | 92 | 73 | 0.21 | 15 | 107 | 0 | 330 | 0 | 0.97 | 425 |
| **11** | | 955 | 0.10 | 96 | 73 | 0.21 | 15 | 111 | 0 | 330 | 0 | 0.97 | 428 |
| **12** | | 955 | 0.10 | 99 | 73 | 0.21 | 16 | 115 | 0 | 330 | 0 | 0.97 | 430 |
| **13** | | 955 | 0.11 | 103 | 73 | 0.22 | 16 | 119 | 0 | 330 | 0 | 0.96 | 433 |
| **14** | | 955 | 0.11 | 107 | 73 | 0.22 | 16 | 123 | 0 | 330 | 0 | 0.96 | 436 |
| **15** | | 955 | 0.12 | 111 | 73 | 0.23 | 17 | 128 | 196 | 330 | 0 | 0.92 | 602 |
| **16** | | 955 | 0.12 | 115 | 73 | 0.23 | 17 | 132 | 0 | 330 | 0 | 0.92 | 423 |
| **17** | | 955 | 0.13 | 120 | 73 | 0.24 | 17 | 137 | 0 | 330 | 0 | 0.91 | 425 |
| **18** | | 955 | 0.13 | 124 | 73 | 0.24 | 18 | 142 | 0 | 330 | 0 | 0.91 | 428 |
| **19** | | 955 | 0.14 | 129 | 73 | 0.25 | 18 | 147 | 0 | 330 | 0 | 0.90 | 430 |
| **20** | | 955 | 0.14 | 134 | 73 | 0.26 | 19 | 152 | 3900 | 330 | 0 | 0.85 | 3706 |
| **21** | | 955 | 0.15 | 139 | 73 | 0.26 | 19 | 158 | 0 | 330 | 0 | 0.84 | 409 |
| **22** | | 955 | 0.15 | 144 | 73 | 0.27 | 19 | 164 | 0 | 330 | 0 | 0.83 | 410 |
| **23** | | 955 | 0.16 | 150 | 73 | 0.27 | 20 | 169 | 0 | 330 | 0 | 0.82 | 412 |
| **24** | | 955 | 0.16 | 155 | 73 | 0.28 | 20 | 176 | 0 | 330 | 0 | 0.82 | 413 |
| **25** | | 955 | 0.17 | 161 | 73 | 0.28 | 21 | 182 | 0 | 330 | 0 | 0.80 | 409 |
| **26** | | 955 | 0.18 | 167 | 73 | 0.29 | 21 | 189 | 0 | 330 | 0 | 0.79 | 411 |
| **27** | | 955 | 0.18 | 174 | 73 | 0.30 | 22 | 195 | 0 | 330 | 0 | 0.79 | 412 |
| **28** | | 955 | 0.19 | 180 | 73 | 0.30 | 22 | 202 | 0 | 330 | 0 | 0.78 | 414 |
| **29** | | 955 | 0.20 | 187 | 73 | 0.31 | 23 | 210 | 0 | 330 | 0 | 0.77 | 416 |
| **30** | | 955 | 0.20 | 194 | 73 | 0.32 | 23 | 217 | 0 | 330 | 1620 | 0.76 | -820 |
| **Total** | 10,483 | 28,647 | 4 | 3,574 | 2,178 | 7 | 513 | 4,088 | 4,096 | 9,900 | 1,620 | 27 | 25,318 |

**Case 33**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 14,043 | | | | | | | | | | | | 14,043 |
| **1** | | 1012 | 0.07 | 70 | 75 | 0.17 | 13 | 83 | 0 | 240 | 0 | 1.00 | 323 |
| **2** | | 1012 | 0.07 | 72 | 75 | 0.17 | 13 | 86 | 0 | 240 | 0 | 1.00 | 326 |
| **3** | | 1012 | 0.07 | 75 | 75 | 0.18 | 13 | 89 | 0 | 240 | 0 | 1.00 | 329 |
| **4** | | 1012 | 0.08 | 78 | 75 | 0.18 | 14 | 92 | 0 | 240 | 0 | 1.00 | 332 |
| **5** | | 1012 | 0.08 | 81 | 75 | 0.18 | 14 | 95 | 0 | 240 | 0 | 1.00 | 335 |
| **6** | | 1012 | 0.08 | 84 | 75 | 0.19 | 14 | 98 | 0 | 240 | 0 | 1.00 | 338 |
| **7** | | 1012 | 0.09 | 87 | 75 | 0.19 | 15 | 102 | 0 | 240 | 0 | 1.00 | 342 |
| **8** | | 1012 | 0.09 | 91 | 75 | 0.20 | 15 | 106 | 0 | 240 | 0 | 1.00 | 346 |
| **9** | | 1012 | 0.09 | 94 | 75 | 0.20 | 15 | 109 | 0 | 240 | 0 | 1.00 | 349 |
| **10** | | 1012 | 0.10 | 98 | 75 | 0.21 | 16 | 113 | 0 | 240 | 0 | 0.97 | 343 |
| **11** | | 1012 | 0.10 | 101 | 75 | 0.21 | 16 | 117 | 0 | 240 | 0 | 0.97 | 346 |
| **12** | | 1012 | 0.10 | 105 | 75 | 0.21 | 16 | 121 | 0 | 240 | 0 | 0.97 | 350 |
| **13** | | 1012 | 0.11 | 109 | 75 | 0.22 | 17 | 126 | 0 | 240 | 0 | 0.96 | 353 |
| **14** | | 1012 | 0.11 | 113 | 75 | 0.22 | 17 | 130 | 0 | 240 | 0 | 0.96 | 356 |
| **15** | | 1012 | 0.12 | 118 | 75 | 0.23 | 17 | 135 | 196 | 240 | 0 | 0.92 | 526 |
| **16** | | 1012 | 0.12 | 122 | 75 | 0.23 | 18 | 140 | 0 | 240 | 0 | 0.92 | 348 |
| **17** | | 1012 | 0.13 | 127 | 75 | 0.24 | 18 | 145 | 0 | 240 | 0 | 0.91 | 351 |
| **18** | | 1012 | 0.13 | 132 | 75 | 0.24 | 18 | 150 | 0 | 240 | 0 | 0.91 | 353 |
| **19** | | 1012 | 0.14 | 137 | 75 | 0.25 | 19 | 156 | 0 | 240 | 0 | 0.90 | 356 |
| **20** | | 1012 | 0.14 | 142 | 75 | 0.26 | 19 | 161 | 2900 | 240 | 0 | 0.85 | 2791 |
| **21** | | 1012 | 0.15 | 147 | 75 | 0.26 | 20 | 167 | 0 | 240 | 0 | 0.84 | 341 |
| **22** | | 1012 | 0.15 | 153 | 75 | 0.27 | 20 | 173 | 0 | 240 | 0 | 0.83 | 343 |
| **23** | | 1012 | 0.16 | 159 | 75 | 0.27 | 21 | 179 | 0 | 240 | 0 | 0.82 | 346 |
| **24** | | 1012 | 0.16 | 165 | 75 | 0.28 | 21 | 186 | 0 | 240 | 0 | 0.82 | 348 |
| **25** | | 1012 | 0.17 | 171 | 75 | 0.28 | 21 | 192 | 0 | 240 | 0 | 0.80 | 346 |
| **26** | | 1012 | 0.18 | 177 | 75 | 0.29 | 22 | 199 | 0 | 240 | 0 | 0.79 | 348 |
| **27** | | 1012 | 0.18 | 184 | 75 | 0.30 | 22 | 207 | 0 | 240 | 0 | 0.79 | 351 |
| **28** | | 1012 | 0.19 | 191 | 75 | 0.30 | 23 | 214 | 0 | 240 | 0 | 0.78 | 353 |
| **29** | | 1012 | 0.20 | 198 | 75 | 0.31 | 23 | 222 | 0 | 240 | 0 | 0.77 | 356 |
| **30** | | 1012 | 0.20 | 206 | 75 | 0.32 | 24 | 230 | 0 | 240 | 1375 | 0.76 | -692 |
| **Total** | 14,043 | 30,362 | 4 | 3,788 | 2,264 | 7 | 534 | 4,322 | 3,096 | 7,200 | 1,375 | 27 | 25,975 |

**Case 34**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 14,463 | | | | | | | | | | | | 14,463 |
| **1** | | 989 | 0.07 | 68 | 73 | 0.17 | 12 | 81 | 0 | 240 | 0 | 1.00 | 321 |
| **2** | | 989 | 0.07 | 71 | 73 | 0.17 | 13 | 83 | 0 | 240 | 0 | 1.00 | 323 |
| **3** | | 989 | 0.07 | 74 | 73 | 0.18 | 13 | 86 | 0 | 240 | 0 | 1.00 | 326 |
| **4** | | 989 | 0.08 | 76 | 73 | 0.18 | 13 | 90 | 0 | 240 | 0 | 1.00 | 330 |
| **5** | | 989 | 0.08 | 79 | 73 | 0.18 | 13 | 93 | 0 | 240 | 0 | 0.99 | 328 |
| **6** | | 989 | 0.08 | 82 | 73 | 0.19 | 14 | 96 | 0 | 240 | 0 | 0.98 | 330 |
| **7** | | 989 | 0.09 | 85 | 73 | 0.19 | 14 | 99 | 0 | 240 | 0 | 0.98 | 333 |
| **8** | | 989 | 0.09 | 89 | 73 | 0.20 | 14 | 103 | 0 | 240 | 0 | 0.98 | 335 |
| **9** | | 989 | 0.09 | 92 | 73 | 0.20 | 15 | 107 | 0 | 240 | 0 | 0.98 | 338 |
| **10** | | 989 | 0.10 | 95 | 73 | 0.21 | 15 | 111 | 0 | 240 | 0 | 0.95 | 332 |
| **11** | | 989 | 0.10 | 99 | 73 | 0.21 | 15 | 114 | 0 | 240 | 0 | 0.94 | 334 |
| **12** | | 989 | 0.10 | 103 | 73 | 0.21 | 16 | 119 | 0 | 240 | 0 | 0.94 | 336 |
| **13** | | 989 | 0.11 | 107 | 73 | 0.22 | 16 | 123 | 0 | 240 | 0 | 0.93 | 338 |
| **14** | | 989 | 0.11 | 111 | 73 | 0.22 | 16 | 127 | 0 | 240 | 0 | 0.93 | 340 |
| **15** | | 989 | 0.12 | 115 | 73 | 0.23 | 17 | 132 | 196 | 240 | 0 | 0.92 | 523 |
| **16** | | 989 | 0.12 | 119 | 73 | 0.23 | 17 | 137 | 0 | 240 | 0 | 0.92 | 345 |
| **17** | | 989 | 0.13 | 124 | 73 | 0.24 | 18 | 141 | 0 | 240 | 0 | 0.91 | 348 |
| **18** | | 989 | 0.13 | 129 | 73 | 0.24 | 18 | 147 | 0 | 240 | 0 | 0.91 | 350 |
| **19** | | 989 | 0.14 | 134 | 73 | 0.25 | 18 | 152 | 0 | 240 | 0 | 0.90 | 353 |
| **20** | | 989 | 0.14 | 139 | 73 | 0.26 | 19 | 157 | 2900 | 240 | 0 | 0.85 | 2788 |
| **21** | | 989 | 0.15 | 144 | 73 | 0.26 | 19 | 163 | 0 | 240 | 0 | 0.84 | 338 |
| **22** | | 989 | 0.15 | 149 | 73 | 0.27 | 20 | 169 | 0 | 240 | 0 | 0.83 | 340 |
| **23** | | 989 | 0.16 | 155 | 73 | 0.27 | 20 | 175 | 0 | 240 | 0 | 0.82 | 342 |
| **24** | | 989 | 0.16 | 161 | 73 | 0.28 | 20 | 181 | 0 | 240 | 0 | 0.82 | 345 |
| **25** | | 989 | 0.17 | 167 | 73 | 0.28 | 21 | 188 | 0 | 240 | 0 | 0.93 | 399 |
| **26** | | 989 | 0.18 | 173 | 73 | 0.29 | 21 | 195 | 0 | 240 | 0 | 0.76 | 329 |
| **27** | | 989 | 0.18 | 180 | 73 | 0.30 | 22 | 202 | 0 | 240 | 0 | 0.75 | 331 |
| **28** | | 989 | 0.19 | 187 | 73 | 0.30 | 22 | 209 | 0 | 240 | 0 | 0.74 | 332 |
| **29** | | 989 | 0.20 | 194 | 73 | 0.31 | 23 | 217 | 0 | 240 | 0 | 0.73 | 334 |
| **30** | | 989 | 0.20 | 201 | 73 | 0.32 | 23 | 225 | 0 | 240 | 1375 | 0.72 | -660 |
| **Total** | 14,463 | 29,677 | 4 | 3,703 | 2,198 | 7 | 518 | 4,221 | 3,096 | 7,200 | 1,375 | 27 | 26,244 |

**Case 35**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 14,945 | | | | | | | | | | | | 14,945 |
| **1** | | 1013 | 0.07 | 70 | 65 | 0.17 | 11 | 81 | 0 | 280 | 0 | 1.00 | 321 |
| **2** | | 1013 | 0.07 | 73 | 65 | 0.17 | 11 | 84 | 0 | 280 | 0 | 1.00 | 323 |
| **3** | | 1013 | 0.07 | 75 | 65 | 0.18 | 12 | 87 | 0 | 280 | 0 | 1.00 | 326 |
| **4** | | 1013 | 0.08 | 78 | 65 | 0.18 | 12 | 90 | 0 | 280 | 0 | 1.00 | 330 |
| **5** | | 1013 | 0.08 | 81 | 65 | 0.18 | 12 | 93 | 0 | 280 | 0 | 1.00 | 333 |
| **6** | | 1013 | 0.08 | 84 | 65 | 0.19 | 12 | 97 | 0 | 280 | 0 | 1.00 | 336 |
| **7** | | 1013 | 0.09 | 87 | 65 | 0.19 | 13 | 100 | 0 | 280 | 0 | 1.00 | 339 |
| **8** | | 1013 | 0.09 | 91 | 65 | 0.20 | 13 | 104 | 0 | 280 | 0 | 1.00 | 343 |
| **9** | | 1013 | 0.09 | 94 | 65 | 0.20 | 13 | 107 | 0 | 280 | 0 | 1.00 | 347 |
| **10** | | 1013 | 0.10 | 98 | 65 | 0.21 | 13 | 111 | 0 | 280 | 0 | 0.97 | 341 |
| **11** | | 1013 | 0.10 | 101 | 65 | 0.21 | 14 | 115 | 0 | 280 | 0 | 0.97 | 344 |
| **12** | | 1013 | 0.10 | 105 | 65 | 0.21 | 14 | 119 | 0 | 280 | 0 | 0.97 | 347 |
| **13** | | 1013 | 0.11 | 109 | 65 | 0.22 | 14 | 124 | 0 | 280 | 0 | 0.96 | 350 |
| **14** | | 1013 | 0.11 | 114 | 65 | 0.22 | 15 | 128 | 0 | 280 | 0 | 0.96 | 353 |
| **15** | | 1013 | 0.12 | 118 | 65 | 0.23 | 15 | 133 | 196 | 280 | 0 | 0.92 | 523 |
| **16** | | 1013 | 0.12 | 122 | 65 | 0.23 | 15 | 138 | 0 | 280 | 0 | 0.92 | 345 |
| **17** | | 1013 | 0.13 | 127 | 65 | 0.24 | 16 | 143 | 0 | 280 | 0 | 0.91 | 348 |
| **18** | | 1013 | 0.13 | 132 | 65 | 0.24 | 16 | 148 | 0 | 280 | 0 | 0.91 | 350 |
| **19** | | 1013 | 0.14 | 137 | 65 | 0.25 | 16 | 153 | 0 | 280 | 0 | 0.90 | 353 |
| **20** | | 1013 | 0.14 | 142 | 65 | 0.26 | 17 | 159 | 3900 | 280 | 0 | 0.85 | 2788 |
| **21** | | 1013 | 0.15 | 147 | 65 | 0.26 | 17 | 164 | 0 | 280 | 0 | 0.84 | 338 |
| **22** | | 1013 | 0.15 | 153 | 65 | 0.27 | 17 | 170 | 0 | 280 | 0 | 0.83 | 340 |
| **23** | | 1013 | 0.16 | 159 | 65 | 0.27 | 18 | 177 | 0 | 280 | 0 | 0.82 | 342 |
| **24** | | 1013 | 0.16 | 165 | 65 | 0.28 | 18 | 183 | 0 | 280 | 0 | 0.82 | 345 |
| **25** | | 1013 | 0.17 | 171 | 65 | 0.28 | 19 | 190 | 0 | 280 | 0 | 0.80 | 342 |
| **26** | | 1013 | 0.18 | 178 | 65 | 0.29 | 19 | 197 | 0 | 280 | 0 | 0.79 | 344 |
| **27** | | 1013 | 0.18 | 184 | 65 | 0.30 | 19 | 204 | 0 | 280 | 0 | 0.79 | 347 |
| **28** | | 1013 | 0.19 | 191 | 65 | 0.30 | 20 | 211 | 0 | 280 | 0 | 0.78 | 349 |
| **29** | | 1013 | 0.20 | 199 | 65 | 0.31 | 20 | 219 | 0 | 280 | 0 | 0.77 | 352 |
| **30** | | 1013 | 0.20 | 206 | 65 | 0.32 | 21 | 227 | 0 | 280 | 1620 | 0.76 | -696 |
| **Total** | 14,945 | 30,388 | 4 | 3,791 | 1,964 | 7 | 463 | 4,254 | 4,096 | 8,400 | 1,620 | 27 | 26,306 |

**Case 36**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 15,043 | | | | | | | | | | | | 15,043 |
| **1** | | 999 | 0.07 | 69 | 65 | 0.17 | 11 | 80 | 0 | 280 | 0 | 1.00 | 360 |
| **2** | | 999 | 0.07 | 72 | 65 | 0.17 | 11 | 83 | 0 | 280 | 0 | 1.00 | 363 |
| **3** | | 999 | 0.07 | 74 | 65 | 0.18 | 12 | 86 | 0 | 280 | 0 | 1.00 | 366 |
| **4** | | 999 | 0.08 | 77 | 65 | 0.18 | 12 | 89 | 0 | 280 | 0 | 1.00 | 369 |
| **5** | | 999 | 0.08 | 80 | 65 | 0.18 | 12 | 92 | 0 | 280 | 0 | 1.00 | 372 |
| **6** | | 999 | 0.08 | 83 | 65 | 0.19 | 12 | 95 | 0 | 280 | 0 | 1.00 | 375 |
| **7** | | 999 | 0.09 | 86 | 65 | 0.19 | 13 | 99 | 0 | 280 | 0 | 1.00 | 379 |
| **8** | | 999 | 0.09 | 90 | 65 | 0.20 | 13 | 102 | 0 | 280 | 0 | 1.00 | 382 |
| **9** | | 999 | 0.09 | 93 | 65 | 0.20 | 13 | 106 | 0 | 280 | 0 | 1.00 | 386 |
| **10** | | 999 | 0.10 | 96 | 65 | 0.21 | 13 | 110 | 0 | 280 | 0 | 0.97 | 379 |
| **11** | | 999 | 0.10 | 100 | 65 | 0.21 | 14 | 114 | 0 | 280 | 0 | 0.97 | 382 |
| **12** | | 999 | 0.10 | 104 | 65 | 0.21 | 14 | 118 | 0 | 280 | 0 | 0.97 | 385 |
| **13** | | 999 | 0.11 | 108 | 65 | 0.22 | 14 | 122 | 0 | 280 | 0 | 0.96 | 388 |
| **14** | | 999 | 0.11 | 112 | 65 | 0.22 | 15 | 127 | 0 | 280 | 0 | 0.96 | 391 |
| **15** | | 999 | 0.12 | 116 | 65 | 0.23 | 15 | 131 | 196 | 280 | 0 | 0.92 | 559 |
| **16** | | 999 | 0.12 | 121 | 65 | 0.23 | 15 | 136 | 0 | 280 | 0 | 0.92 | 381 |
| **17** | | 999 | 0.13 | 125 | 65 | 0.24 | 16 | 141 | 0 | 280 | 0 | 0.91 | 383 |
| **18** | | 999 | 0.13 | 130 | 65 | 0.24 | 16 | 146 | 0 | 280 | 0 | 0.91 | 386 |
| **19** | | 999 | 0.14 | 135 | 65 | 0.25 | 16 | 151 | 0 | 280 | 0 | 0.90 | 389 |
| **20** | | 999 | 0.14 | 140 | 65 | 0.26 | 17 | 157 | 3900 | 280 | 0 | 0.85 | 3667 |
| **21** | | 999 | 0.15 | 145 | 65 | 0.26 | 17 | 162 | 0 | 280 | 0 | 0.84 | 371 |
| **22** | | 999 | 0.15 | 151 | 65 | 0.27 | 17 | 168 | 0 | 280 | 0 | 0.83 | 373 |
| **23** | | 999 | 0.16 | 157 | 65 | 0.27 | 18 | 174 | 0 | 280 | 0 | 0.82 | 375 |
| **24** | | 999 | 0.16 | 163 | 65 | 0.28 | 18 | 181 | 0 | 280 | 0 | 0.82 | 377 |
| **25** | | 999 | 0.17 | 169 | 65 | 0.28 | 19 | 187 | 0 | 280 | 0 | 0.80 | 374 |
| **26** | | 999 | 0.18 | 175 | 65 | 0.29 | 19 | 194 | 0 | 280 | 0 | 0.79 | 376 |
| **27** | | 999 | 0.18 | 182 | 65 | 0.30 | 19 | 201 | 0 | 280 | 0 | 0.79 | 378 |
| **28** | | 999 | 0.19 | 189 | 65 | 0.30 | 20 | 209 | 0 | 280 | 0 | 0.78 | 380 |
| **29** | | 999 | 0.20 | 196 | 65 | 0.31 | 20 | 216 | 0 | 280 | 0 | 0.77 | 383 |
| **30** | | 999 | 0.20 | 203 | 65 | 0.32 | 21 | 224 | 0 | 280 | 1620 | 0.76 | -853 |
| **Total** | 15,043 | 29,980 | 4 | 3,741 | 1,959 | 7 | 462 | 4,202 | 4,096 | 8,400 | 1,620 | 27 | 28,617 |

**Case 37**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 15,365 | | | | | | | | | | | | 15,365 |
| **1** | | 990 | 0.07 | 68 | 64 | 0.17 | 11 | 79 | 0 | 280 | 0 | 1.00 | 359 |
| **2** | | 990 | 0.07 | 71 | 64 | 0.17 | 11 | 82 | 0 | 280 | 0 | 1.00 | 362 |
| **3** | | 990 | 0.07 | 74 | 64 | 0.18 | 11 | 85 | 0 | 280 | 0 | 1.00 | 365 |
| **4** | | 990 | 0.08 | 76 | 64 | 0.18 | 11 | 88 | 0 | 280 | 0 | 1.00 | 368 |
| **5** | | 990 | 0.08 | 79 | 64 | 0.18 | 12 | 91 | 0 | 280 | 0 | 1.00 | 371 |
| **6** | | 990 | 0.08 | 82 | 64 | 0.19 | 12 | 94 | 0 | 280 | 0 | 1.00 | 374 |
| **7** | | 990 | 0.09 | 85 | 64 | 0.19 | 12 | 98 | 0 | 280 | 0 | 1.00 | 378 |
| **8** | | 990 | 0.09 | 89 | 64 | 0.20 | 13 | 101 | 0 | 280 | 0 | 1.00 | 381 |
| **9** | | 990 | 0.09 | 92 | 64 | 0.20 | 13 | 105 | 0 | 280 | 0 | 1.00 | 385 |
| **10** | | 990 | 0.10 | 96 | 64 | 0.21 | 13 | 109 | 0 | 280 | 0 | 0.97 | 378 |
| **11** | | 990 | 0.10 | 99 | 64 | 0.21 | 13 | 113 | 0 | 280 | 0 | 0.97 | 381 |
| **12** | | 990 | 0.10 | 103 | 64 | 0.21 | 14 | 117 | 0 | 280 | 0 | 0.97 | 384 |
| **13** | | 990 | 0.11 | 107 | 64 | 0.22 | 14 | 121 | 0 | 280 | 0 | 0.96 | 387 |
| **14** | | 990 | 0.11 | 111 | 64 | 0.22 | 14 | 125 | 0 | 280 | 0 | 0.96 | 390 |
| **15** | | 990 | 0.12 | 115 | 64 | 0.23 | 15 | 130 | 196 | 280 | 0 | 0.92 | 558 |
| **16** | | 990 | 0.12 | 120 | 64 | 0.23 | 15 | 134 | 0 | 280 | 0 | 0.92 | 380 |
| **17** | | 990 | 0.13 | 124 | 64 | 0.24 | 15 | 139 | 0 | 280 | 0 | 0.91 | 382 |
| **18** | | 990 | 0.13 | 129 | 64 | 0.24 | 16 | 144 | 0 | 280 | 0 | 0.91 | 384 |
| **19** | | 990 | 0.14 | 134 | 64 | 0.25 | 16 | 150 | 0 | 280 | 0 | 0.90 | 387 |
| **20** | | 990 | 0.14 | 139 | 64 | 0.26 | 16 | 155 | 3900 | 280 | 0 | 0.85 | 3666 |
| **21** | | 990 | 0.15 | 144 | 64 | 0.26 | 17 | 161 | 0 | 280 | 0 | 0.84 | 370 |
| **22** | | 990 | 0.15 | 150 | 64 | 0.27 | 17 | 167 | 0 | 280 | 0 | 0.83 | 371 |
| **23** | | 990 | 0.16 | 155 | 64 | 0.27 | 17 | 173 | 0 | 280 | 0 | 0.82 | 373 |
| **24** | | 990 | 0.16 | 161 | 64 | 0.28 | 18 | 179 | 0 | 280 | 0 | 0.82 | 375 |
| **25** | | 990 | 0.17 | 167 | 64 | 0.28 | 18 | 185 | 0 | 280 | 0 | 0.80 | 372 |
| **26** | | 990 | 0.18 | 174 | 64 | 0.29 | 19 | 192 | 0 | 280 | 0 | 0.79 | 374 |
| **27** | | 990 | 0.18 | 180 | 64 | 0.30 | 19 | 199 | 0 | 280 | 0 | 0.79 | 376 |
| **28** | | 990 | 0.19 | 187 | 64 | 0.30 | 19 | 206 | 0 | 280 | 0 | 0.78 | 378 |
| **29** | | 990 | 0.20 | 194 | 64 | 0.31 | 20 | 214 | 0 | 280 | 0 | 0.77 | 381 |
| **30** | | 990 | 0.20 | 202 | 64 | 0.32 | 20 | 222 | 0 | 280 | 1620 | 0.76 | -855 |
| **Total** | 15,365 | 29,710 | 4 | 3,707 | 1,911 | 7 | 450 | 4,157 | 4,096 | 8,400 | 1,620 | 27 | 28,899 |

**Case 38**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 15,463 | | | | | | | | | | | | 15,463 |
| **1** | | 977 | 0.07 | 67 | 64 | 0.17 | 11 | 78 | 0 | 280 | 0 | 1.00 | 358 |
| **2** | | 977 | 0.07 | 70 | 64 | 0.17 | 11 | 81 | 0 | 280 | 0 | 1.00 | 361 |
| **3** | | 977 | 0.07 | 73 | 64 | 0.18 | 11 | 84 | 0 | 280 | 0 | 1.00 | 364 |
| **4** | | 977 | 0.08 | 75 | 64 | 0.18 | 11 | 87 | 0 | 280 | 0 | 1.00 | 367 |
| **5** | | 977 | 0.08 | 78 | 64 | 0.18 | 12 | 90 | 0 | 280 | 0 | 1.00 | 370 |
| **6** | | 977 | 0.08 | 81 | 64 | 0.19 | 12 | 93 | 0 | 280 | 0 | 1.00 | 373 |
| **7** | | 977 | 0.09 | 84 | 64 | 0.19 | 12 | 97 | 0 | 280 | 0 | 1.00 | 377 |
| **8** | | 977 | 0.09 | 87 | 64 | 0.20 | 12 | 100 | 0 | 280 | 0 | 1.00 | 380 |
| **9** | | 977 | 0.09 | 91 | 64 | 0.20 | 13 | 104 | 0 | 280 | 0 | 1.00 | 384 |
| **10** | | 977 | 0.10 | 94 | 64 | 0.21 | 13 | 107 | 0 | 280 | 0 | 0.97 | 377 |
| **11** | | 977 | 0.10 | 98 | 64 | 0.21 | 13 | 111 | 0 | 280 | 0 | 0.97 | 379 |
| **12** | | 977 | 0.10 | 102 | 64 | 0.21 | 14 | 115 | 0 | 280 | 0 | 0.97 | 382 |
| **13** | | 977 | 0.11 | 105 | 64 | 0.22 | 14 | 119 | 0 | 280 | 0 | 0.96 | 385 |
| **14** | | 977 | 0.11 | 109 | 64 | 0.22 | 14 | 124 | 0 | 280 | 0 | 0.96 | 388 |
| **15** | | 977 | 0.12 | 114 | 64 | 0.23 | 15 | 128 | 196 | 280 | 0 | 0.92 | 556 |
| **16** | | 977 | 0.12 | 118 | 64 | 0.23 | 15 | 133 | 0 | 280 | 0 | 0.92 | 378 |
| **17** | | 977 | 0.13 | 122 | 64 | 0.24 | 15 | 138 | 0 | 280 | 0 | 0.91 | 380 |
| **18** | | 977 | 0.13 | 127 | 64 | 0.24 | 16 | 143 | 0 | 280 | 0 | 0.91 | 383 |
| **19** | | 977 | 0.14 | 132 | 64 | 0.25 | 16 | 148 | 0 | 280 | 0 | 0.90 | 385 |
| **20** | | 977 | 0.14 | 137 | 64 | 0.26 | 16 | 153 | 3900 | 280 | 0 | 0.85 | 3664 |
| **21** | | 977 | 0.15 | 142 | 64 | 0.26 | 17 | 159 | 0 | 280 | 0 | 0.84 | 368 |
| **22** | | 977 | 0.15 | 147 | 64 | 0.27 | 17 | 164 | 0 | 280 | 0 | 0.83 | 370 |
| **23** | | 977 | 0.16 | 153 | 64 | 0.27 | 17 | 170 | 0 | 280 | 0 | 0.82 | 371 |
| **24** | | 977 | 0.16 | 159 | 64 | 0.28 | 18 | 177 | 0 | 280 | 0 | 0.82 | 373 |
| **25** | | 977 | 0.17 | 165 | 64 | 0.28 | 18 | 183 | 0 | 280 | 0 | 0.80 | 370 |
| **26** | | 977 | 0.18 | 171 | 64 | 0.29 | 18 | 190 | 0 | 280 | 0 | 0.79 | 372 |
| **27** | | 977 | 0.18 | 178 | 64 | 0.30 | 19 | 197 | 0 | 280 | 0 | 0.79 | 374 |
| **28** | | 977 | 0.19 | 184 | 64 | 0.30 | 19 | 204 | 0 | 280 | 0 | 0.78 | 376 |
| **29** | | 977 | 0.20 | 191 | 64 | 0.31 | 20 | 211 | 0 | 280 | 0 | 0.77 | 379 |
| **30** | | 977 | 0 | 199 | 64 | 0.32 | 20 | 219 | 0 | 280 | 1620 | 0.76 | -857 |
| **Total** | 15,463 | 29,296 | 4 | 3,655 | 1,906 | 7 | 449 | 4,104 | 4,096 | 8,400 | 1,620 | 27 | 28,951 |

| Case 39 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 16,218 | | | | | | | | | | | | 16,218 |
| **1** | | 1014 | 0.07 | 70 | 69 | 0.17 | 12 | 82 | 0 | 371 | 0 | 1.00 | 452 |
| **2** | | 1014 | 0.07 | 73 | 69 | 0.17 | 12 | 84 | 0 | 371 | 0 | 1.00 | 455 |
| **3** | | 1014 | 0.07 | 75 | 69 | 0.18 | 12 | 87 | 0 | 371 | 0 | 1.00 | 458 |
| **4** | | 1014 | 0.08 | 78 | 69 | 0.18 | 12 | 91 | 0 | 371 | 0 | 1.00 | 461 |
| **5** | | 1014 | 0.08 | 81 | 69 | 0.18 | 13 | 94 | 0 | 371 | 0 | 1.00 | 464 |
| **6** | | 1014 | 0.08 | 84 | 69 | 0.19 | 13 | 97 | 0 | 371 | 0 | 1.00 | 468 |
| **7** | | 1014 | 0.09 | 87 | 69 | 0.19 | 13 | 101 | 0 | 371 | 0 | 1.00 | 471 |
| **8** | | 1014 | 0.09 | 91 | 69 | 0.20 | 14 | 104 | 0 | 371 | 0 | 1.00 | 475 |
| **9** | | 1014 | 0.09 | 94 | 69 | 0.20 | 14 | 108 | 0 | 371 | 0 | 1.00 | 479 |
| **10** | | 1014 | 0.10 | 98 | 69 | 0.21 | 14 | 112 | 0 | 371 | 0 | 0.97 | 469 |
| **11** | | 1014 | 0.10 | 102 | 69 | 0.21 | 14 | 116 | 0 | 371 | 0 | 0.97 | 472 |
| **12** | | 1014 | 0.10 | 105 | 69 | 0.21 | 15 | 120 | 0 | 371 | 0 | 0.97 | 474 |
| **13** | | 1014 | 0.11 | 109 | 69 | 0.22 | 15 | 124 | 0 | 371 | 0 | 0.96 | 477 |
| **14** | | 1014 | 0.11 | 114 | 69 | 0.22 | 15 | 129 | 0 | 371 | 0 | 0.96 | 480 |
| **15** | | 1014 | 0.12 | 118 | 69 | 0.23 | 16 | 134 | 196 | 371 | 0 | 0.92 | 644 |
| **16** | | 1014 | 0.12 | 122 | 69 | 0.23 | 16 | 138 | 0 | 371 | 0 | 0.92 | 466 |
| **17** | | 1014 | 0.13 | 127 | 69 | 0.24 | 16 | 143 | 0 | 371 | 0 | 0.91 | 468 |
| **18** | | 1014 | 0.13 | 132 | 69 | 0.24 | 17 | 149 | 0 | 371 | 0 | 0.91 | 470 |
| **19** | | 1014 | 0.14 | 137 | 69 | 0.25 | 17 | 154 | 0 | 371 | 0 | 0.90 | 473 |
| **20** | | 1014 | 0.14 | 142 | 69 | 0.26 | 18 | 160 | 2900 | 371 | 0 | 0.85 | 2901 |
| **21** | | 1014 | 0.15 | 147 | 69 | 0.26 | 18 | 165 | 0 | 371 | 0 | 0.84 | 449 |
| **22** | | 1014 | 0.15 | 153 | 69 | 0.27 | 18 | 171 | 0 | 371 | 0 | 0.83 | 451 |
| **23** | | 1014 | 0.16 | 159 | 69 | 0.27 | 19 | 178 | 0 | 371 | 0 | 0.82 | 452 |
| **24** | | 1014 | 0.16 | 165 | 69 | 0.28 | 19 | 184 | 0 | 371 | 0 | 0.82 | 453 |
| **25** | | 1014 | 0.17 | 171 | 69 | 0.28 | 20 | 191 | 0 | 371 | 0 | 0.80 | 449 |
| **26** | | 1014 | 0.18 | 178 | 69 | 0.29 | 20 | 198 | 0 | 371 | 0 | 0.79 | 450 |
| **27** | | 1014 | 0.18 | 184 | 69 | 0.30 | 20 | 205 | 0 | 371 | 0 | 0.79 | 452 |
| **28** | | 1014 | 0.19 | 191 | 69 | 0.30 | 21 | 212 | 0 | 371 | 0 | 0.78 | 454 |
| **29** | | 1014 | 0.20 | 199 | 69 | 0.31 | 21 | 220 | 0 | 371 | 0 | 0.77 | 455 |
| **30** | | 1014 | 0.20 | 206 | 69 | 0.32 | 22 | 228 | 0 | 371 | 1455 | 0.76 | -655 |
| **Total** | 16,218 | 30,411 | 4 | 3,794 | 2,060 | 7 | 485 | 4,280 | 3,096 | 11,115 | 1,455 | 27 | 31,606 |

| Case 40 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 17,851 | | | | | | | | | | | | 17,851 |
| **1** | | 782 | 0.07 | 54 | 216 | 0.17 | 36 | 90 | 0 | 240 | 0 | 1.00 | 330 |
| **2** | | 782 | 0.07 | 56 | 216 | 0.17 | 37 | 93 | 0 | 240 | 0 | 1.00 | 333 |
| **3** | | 782 | 0.07 | 58 | 216 | 0.18 | 38 | 96 | 0 | 240 | 0 | 1.00 | 336 |
| **4** | | 782 | 0.08 | 60 | 216 | 0.18 | 39 | 99 | 0 | 240 | 0 | 1.00 | 339 |
| **5** | | 782 | 0.08 | 63 | 216 | 0.18 | 40 | 102 | 0 | 240 | 0 | 1.00 | 342 |
| **6** | | 782 | 0.08 | 65 | 216 | 0.19 | 41 | 106 | 0 | 240 | 0 | 1.00 | 346 |
| **7** | | 782 | 0.09 | 67 | 216 | 0.19 | 42 | 109 | 0 | 240 | 0 | 1.00 | 349 |
| **8** | | 782 | 0.09 | 70 | 216 | 0.20 | 42 | 112 | 0 | 240 | 0 | 1.00 | 352 |
| **9** | | 782 | 0.09 | 73 | 216 | 0.20 | 43 | 116 | 0 | 240 | 0 | 1.00 | 356 |
| **10** | | 782 | 0.10 | 75 | 216 | 0.21 | 44 | 120 | 0 | 240 | 0 | 0.97 | 350 |
| **11** | | 782 | 0.10 | 78 | 216 | 0.21 | 45 | 124 | 0 | 240 | 0 | 0.97 | 353 |
| **12** | | 782 | 0.10 | 81 | 216 | 0.21 | 46 | 128 | 0 | 240 | 0 | 0.97 | 355 |
| **13** | | 782 | 0.11 | 84 | 216 | 0.22 | 47 | 132 | 0 | 240 | 0 | 0.96 | 358 |
| **14** | | 782 | 0.11 | 88 | 216 | 0.22 | 48 | 136 | 0 | 240 | 0 | 0.96 | 362 |
| **15** | | 782 | 0.12 | 91 | 216 | 0.23 | 49 | 140 | 196 | 240 | 0 | 0.92 | 530 |
| **16** | | 782 | 0.12 | 94 | 216 | 0.23 | 51 | 145 | 0 | 240 | 0 | 0.92 | 353 |
| **17** | | 782 | 0.13 | 98 | 216 | 0.24 | 52 | 150 | 0 | 240 | 0 | 0.91 | 355 |
| **18** | | 782 | 0.13 | 102 | 216 | 0.24 | 53 | 154 | 0 | 240 | 0 | 0.91 | 357 |
| **19** | | 782 | 0.14 | 106 | 216 | 0.25 | 54 | 159 | 0 | 240 | 0 | 0.90 | 360 |
| **20** | | 782 | 0.14 | 110 | 216 | 0.26 | 55 | 165 | 2900 | 240 | 0 | 0.85 | 2794 |
| **21** | | 782 | 0.15 | 114 | 216 | 0.26 | 56 | 170 | 0 | 240 | 0 | 0.84 | 344 |
| **22** | | 782 | 0.15 | 118 | 216 | 0.27 | 58 | 176 | 0 | 240 | 0 | 0.83 | 346 |
| **23** | | 782 | 0.16 | 123 | 216 | 0.27 | 59 | 181 | 0 | 240 | 0 | 0.82 | 347 |
| **24** | | 782 | 0.16 | 127 | 216 | 0.28 | 60 | 187 | 0 | 240 | 0 | 0.82 | 349 |
| **25** | | 782 | 0.17 | 132 | 216 | 0.28 | 61 | 193 | 0 | 240 | 0 | 0.80 | 347 |
| **26** | | 782 | 0.18 | 137 | 216 | 0.29 | 63 | 200 | 0 | 240 | 0 | 0.79 | 348 |
| **27** | | 782 | 0.18 | 142 | 216 | 0.30 | 64 | 206 | 0 | 240 | 0 | 0.79 | 351 |
| **28** | | 782 | 0.19 | 148 | 216 | 0.30 | 66 | 213 | 0 | 240 | 0 | 0.78 | 353 |
| **29** | | 782 | 0.20 | 153 | 216 | 0.31 | 67 | 220 | 0 | 240 | 0 | 0.77 | 355 |
| **30** | | 782 | 0.20 | 159 | 216 | 0 | 69 | 228 | 0 | 240 | 1375 | 0.76 | -694 |
| **Total** | 17,851 | 23,459 | 4 | 2,927 | 6,472 | 7 | 1,526 | 4,453 | 3,096 | 7,200 | 1,375 | 27 | 29,909 |

| Case 41 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| 0 | 21,026 | | | | | | | | | | | | 21,026 |
| 1 | | 771 | 0.07 | 53 | 63 | 0.17 | 11 | 64 | 0 | 411 | 0 | 1.00 | 474 |
| 2 | | 771 | 0.07 | 55 | 63 | 0.17 | 11 | 66 | 0 | 411 | 0 | 1.00 | 477 |
| 3 | | 771 | 0.07 | 57 | 63 | 0.18 | 11 | 68 | 0 | 411 | 0 | 1.00 | 479 |
| 4 | | 771 | 0.08 | 60 | 63 | 0.18 | 11 | 71 | 0 | 411 | 0 | 1.00 | 481 |
| 5 | | 771 | 0.08 | 62 | 63 | 0.18 | 12 | 73 | 0 | 411 | 0 | 1.00 | 484 |
| 6 | | 771 | 0.08 | 64 | 63 | 0.19 | 12 | 76 | 0 | 411 | 0 | 1.00 | 486 |
| 7 | | 771 | 0.09 | 67 | 63 | 0.19 | 12 | 79 | 0 | 411 | 0 | 1.00 | 489 |
| 8 | | 771 | 0.09 | 69 | 63 | 0.20 | 12 | 81 | 0 | 411 | 0 | 1.00 | 492 |
| 9 | | 771 | 0.09 | 72 | 63 | 0.20 | 13 | 84 | 0 | 411 | 0 | 1.00 | 495 |
| 10 | | 771 | 0.10 | 74 | 63 | 0.21 | 13 | 87 | 0 | 411 | 0 | 0.97 | 484 |
| 11 | | 771 | 0.10 | 77 | 63 | 0.21 | 13 | 90 | 0 | 411 | 0 | 0.97 | 486 |
| 12 | | 771 | 0.10 | 80 | 63 | 0.21 | 13 | 94 | 0 | 411 | 0 | 0.97 | 488 |
| 13 | | 771 | 0.11 | 83 | 63 | 0.22 | 14 | 97 | 0 | 411 | 0 | 0.96 | 489 |
| 14 | | 771 | 0.11 | 86 | 63 | 0.22 | 14 | 100 | 0 | 411 | 0 | 0.96 | 491 |
| 15 | | 771 | 0.12 | 90 | 63 | 0.23 | 14 | 104 | 196 | 411 | 0 | 0.92 | 654 |
| 16 | | 771 | 0.12 | 93 | 63 | 0.23 | 15 | 108 | 0 | 411 | 0 | 0.92 | 475 |
| 17 | | 771 | 0.13 | 97 | 63 | 0.24 | 15 | 112 | 0 | 411 | 0 | 0.91 | 476 |
| 18 | | 771 | 0.13 | 100 | 63 | 0.24 | 15 | 116 | 0 | 411 | 0 | 0.91 | 477 |
| 19 | | 771 | 0.14 | 104 | 63 | 0.25 | 16 | 120 | 0 | 411 | 0 | 0.90 | 478 |
| 20 | | 771 | 0.14 | 108 | 63 | 0.26 | 16 | 124 | 3900 | 411 | 0 | 0.85 | 3750 |
| 21 | | 771 | 0.15 | 112 | 63 | 0.26 | 16 | 129 | 0 | 411 | 0 | 0.84 | 452 |
| 22 | | 771 | 0.15 | 116 | 63 | 0.27 | 17 | 133 | 0 | 411 | 0 | 0.83 | 452 |
| 23 | | 771 | 0.16 | 121 | 63 | 0.27 | 17 | 138 | 0 | 411 | 0 | 0.82 | 452 |
| 24 | | 771 | 0.16 | 125 | 63 | 0.28 | 17 | 143 | 0 | 411 | 0 | 0.82 | 453 |
| 25 | | 771 | 0.17 | 130 | 63 | 0.28 | 18 | 148 | 0 | 411 | 0 | 0.80 | 447 |
| 26 | | 771 | 0.18 | 135 | 63 | 0.29 | 18 | 153 | 0 | 411 | 0 | 0.79 | 447 |
| 27 | | 771 | 0.18 | 140 | 63 | 0.30 | 19 | 159 | 0 | 411 | 0 | 0.79 | 447 |
| 28 | | 771 | 0.19 | 146 | 63 | 0.30 | 19 | 165 | 0 | 411 | 0 | 0.78 | 448 |
| 29 | | 771 | 0.20 | 151 | 63 | 0.31 | 19 | 171 | 0 | 411 | 0 | 0.77 | 448 |
| 30 | | 771 | 0.20 | 157 | 63 | 0.32 | 20 | 177 | 0 | 411 | 1700 | 0.76 | -850 |
| Total | 21,026 | 23,139 | 4 | 2,887 | 1,880 | 7 | 443 | 3,330 | 4,096 | 12,315 | 1,700 | 27 | 37,325 |

| Case 42 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| 0 | 21,446 | | | | | | | | | | | | 21,446 |
| 1 | | 744 | 0.07 | 51 | 61 | 0.17 | 10 | 62 | 0 | 411 | 0 | 1.00 | 472 |
| 2 | | 744 | 0.07 | 53 | 61 | 0.17 | 10 | 64 | 0 | 411 | 0 | 1.00 | 474 |
| 3 | | 744 | 0.07 | 55 | 61 | 0.18 | 11 | 66 | 0 | 411 | 0 | 1.00 | 477 |
| 4 | | 744 | 0.08 | 57 | 61 | 0.18 | 11 | 68 | 0 | 411 | 0 | 1.00 | 479 |
| 5 | | 744 | 0.08 | 60 | 61 | 0.18 | 11 | 71 | 0 | 411 | 0 | 1.00 | 481 |
| 6 | | 744 | 0.08 | 62 | 61 | 0.19 | 11 | 73 | 0 | 411 | 0 | 1.00 | 484 |
| 7 | | 744 | 0.09 | 64 | 61 | 0.19 | 12 | 76 | 0 | 411 | 0 | 1.00 | 486 |
| 8 | | 744 | 0.09 | 67 | 61 | 0.20 | 12 | 79 | 0 | 411 | 0 | 1.00 | 489 |
| 9 | | 744 | 0.09 | 69 | 61 | 0.20 | 12 | 81 | 0 | 411 | 0 | 1.00 | 492 |
| 10 | | 744 | 0.10 | 72 | 61 | 0.21 | 12 | 84 | 0 | 411 | 0 | 0.97 | 481 |
| 11 | | 744 | 0.10 | 75 | 61 | 0.21 | 13 | 87 | 0 | 411 | 0 | 0.97 | 483 |
| 12 | | 744 | 0.10 | 77 | 61 | 0.21 | 13 | 90 | 0 | 411 | 0 | 0.97 | 484 |
| 13 | | 744 | 0.11 | 80 | 61 | 0.22 | 13 | 94 | 0 | 411 | 0 | 0.96 | 486 |
| 14 | | 744 | 0.11 | 83 | 61 | 0.22 | 14 | 97 | 0 | 411 | 0 | 0.96 | 488 |
| 15 | | 744 | 0.12 | 87 | 61 | 0.23 | 14 | 101 | | 411 | 0 | 0.92 | 471 |
| 16 | | 744 | 0.12 | 90 | 61 | 0.23 | 14 | 104 | 0 | 411 | 0 | 0.92 | 471 |
| 17 | | 744 | 0.13 | 93 | 61 | 0.24 | 15 | 108 | 0 | 411 | 0 | 0.91 | 472 |
| 18 | | 744 | 0.13 | 97 | 61 | 0.24 | 15 | 112 | 0 | 411 | 0 | 0.91 | 473 |
| 19 | | 744 | 0.14 | 101 | 61 | 0.25 | 15 | 116 | 0 | 411 | 0 | 0.90 | 474 |
| 20 | | 744 | 0.14 | 104 | 61 | 0.26 | 16 | 120 | 3900 | 411 | 0 | 0.85 | 3746 |
| 21 | | 744 | 0.15 | 108 | 61 | 0.26 | 16 | 124 | 0 | 411 | 0 | 0.84 | 448 |
| 22 | | 744 | 0.15 | 112 | 61 | 0.27 | 16 | 129 | 0 | 411 | 0 | 0.83 | 448 |
| 23 | | 744 | 0.16 | 117 | 61 | 0.27 | 17 | 133 | 0 | 411 | 0 | 0.82 | 448 |
| 24 | | 744 | 0.16 | 121 | 61 | 0.28 | 17 | 138 | 0 | 411 | 0 | 0.82 | 449 |
| 25 | | 744 | 0.17 | 126 | 61 | 0.28 | 17 | 143 | 0 | 411 | 0 | 0.80 | 442 |
| 26 | | 744 | 0.18 | 131 | 61 | 0.29 | 18 | 148 | 0 | 411 | 0 | 0.79 | 443 |
| 27 | | 744 | 0.18 | 135 | 61 | 0.30 | 18 | 154 | 0 | 411 | 0 | 0.79 | 443 |
| 28 | | 744 | 0.19 | 141 | 61 | 0.30 | 18 | 159 | 0 | 411 | 0 | 0.78 | 443 |
| 29 | | 744 | 0.20 | 146 | 61 | 0.31 | 19 | 165 | 0 | 411 | 0 | 0.77 | 444 |
| 30 | | 744 | 0.20 | 151 | 61 | 0.32 | 19 | 171 | 0 | 411 | 1700 | 0.76 | -855 |
| Total | 21,446 | 22,334 | 4 | 2,787 | 1,825 | 7 | 430 | 3,217 | 3,900 | 12,315 | 1,700 | 27 | 37,465 |

**LCCA of the reference building of the first and ground floor under the extended school curriculum during the afternoon (7:30-13:35, 14:45-17:45).**

| Reference first floor | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | - | | | | | | | | | | | | - |
| **1** | | 3857 | 0.07 | 266 | 256 | 0.17 | 43 | 309 | 0 | 190 | 0 | 1.00 | 499 |
| **2** | | 3857 | 0.07 | 276 | 256 | 0.17 | 44 | 320 | 0 | 190 | 0 | 1.00 | 510 |
| **3** | | 3857 | 0.07 | 287 | 256 | 0.18 | 45 | 332 | 0 | 190 | 0 | 1.00 | 522 |
| **4** | | 3857 | 0.08 | 298 | 256 | 0.18 | 46 | 344 | 0 | 190 | 0 | 1.00 | 534 |
| **5** | | 3857 | 0.08 | 309 | 256 | 0.18 | 47 | 356 | 1120 | 190 | 0 | 1.00 | 1666 |
| **6** | | 3857 | 0.08 | 321 | 256 | 0.19 | 48 | 369 | 0 | 190 | 0 | 1.00 | 559 |
| **7** | | 3857 | 0.09 | 333 | 256 | 0.19 | 49 | 382 | 0 | 190 | 0 | 1.00 | 572 |
| **8** | | 3857 | 0.09 | 346 | 256 | 0.20 | 50 | 396 | 0 | 190 | 0 | 1.00 | 586 |
| **9** | | 3857 | 0.09 | 359 | 256 | 0.20 | 52 | 410 | 0 | 190 | 0 | 1.00 | 600 |
| **10** | | 3857 | 0.10 | 372 | 256 | 0.21 | 53 | 425 | 196 | 190 | 0 | 0.97 | 788 |
| **11** | | 3857 | 0.10 | 386 | 256 | 0.21 | 54 | 440 | 0 | 190 | 0 | 0.97 | 611 |
| **12** | | 3857 | 0.10 | 401 | 256 | 0.21 | 55 | 456 | 0 | 190 | 0 | 0.97 | 625 |
| **13** | | 3857 | 0.11 | 416 | 256 | 0.22 | 56 | 473 | 0 | 190 | 0 | 0.96 | 639 |
| **14** | | 3857 | 0.11 | 432 | 256 | 0.22 | 57 | 490 | 0 | 190 | 0 | 0.96 | 654 |
| **15** | | 3857 | 0.12 | 449 | 256 | 0.23 | 59 | 507 | 196 | 190 | 0 | 0.92 | 822 |
| **16** | | 3857 | 0.12 | 466 | 256 | 0.23 | 60 | 526 | 0 | 190 | 0 | 0.92 | 655 |
| **17** | | 3857 | 0.13 | 483 | 256 | 0.24 | 61 | 545 | 0 | 190 | 0 | 0.91 | 669 |
| **18** | | 3857 | 0.13 | 502 | 256 | 0.24 | 63 | 564 | 0 | 190 | 0 | 0.91 | 683 |
| **19** | | 3857 | 0.14 | 521 | 256 | 0.25 | 64 | 585 | 0 | 190 | 0 | 0.90 | 698 |
| **20** | | 3857 | 0.14 | 541 | 256 | 0.26 | 65 | 606 | 196 | 190 | 0 | 0.85 | 839 |
| **21** | | 3857 | 0.15 | 561 | 256 | 0.26 | 67 | 628 | 0 | 190 | 0 | 0.84 | 686 |
| **22** | | 3857 | 0.15 | 582 | 256 | 0.27 | 68 | 651 | 0 | 190 | 0 | 0.83 | 699 |
| **23** | | 3857 | 0.16 | 605 | 256 | 0.27 | 70 | 674 | 0 | 190 | 0 | 0.82 | 713 |
| **24** | | 3857 | 0.16 | 628 | 256 | 0.28 | 71 | 699 | 0 | 190 | 0 | 0.82 | 727 |
| **25** | | 3857 | 0.17 | 651 | 256 | 0.28 | 73 | 724 | 1120 | 190 | 0 | 0.80 | 1626 |
| **26** | | 3857 | 0.18 | 676 | 256 | 0.29 | 75 | 751 | 0 | 190 | 0 | 0.79 | 745 |
| **27** | | 3857 | 0.18 | 702 | 256 | 0.30 | 76 | 778 | 0 | 190 | 0 | 0.79 | 760 |
| **28** | | 3857 | 0.19 | 728 | 256 | 0.30 | 78 | 806 | 0 | 190 | 0 | 0.78 | 775 |
| **29** | | 3857 | 0.20 | 756 | 256 | 0.31 | 80 | 836 | 0 | 190 | 0 | 0.77 | 791 |
| **30** | | 3857 | 0.20 | 785 | 256 | 0 | 81 | 866 | 0 | 190 | 0 | 0.76 | 807 |
| **Total** | - | 115,709 | 4 | 14,437 | 7,685 | 7 | 1,812 | 16,248 | 2,827 | 5,700 | 0 | 27 | 22,063 |

| Reference ground floor | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh/y) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh/y) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | - | | | | | | | | | | | | - |
| **1** | | 3859 | 0.07 | 266 | 179 | 0.17 | 30 | 297 | 0 | 190 | 0 | 1.00 | 487 |
| **2** | | 3859 | 0.07 | 276 | 179 | 0.17 | 31 | 307 | 0 | 190 | 0 | 1.00 | 497 |
| **3** | | 3859 | 0.07 | 287 | 179 | 0.18 | 32 | 319 | 0 | 190 | 0 | 1.00 | 509 |
| **4** | | 3859 | 0.08 | 298 | 179 | 0.18 | 32 | 330 | 0 | 190 | 0 | 1.00 | 520 |
| **5** | | 3859 | 0.08 | 309 | 179 | 0.18 | 33 | 342 | 1120 | 190 | 0 | 1.00 | 1652 |
| **6** | | 3859 | 0.08 | 321 | 179 | 0.19 | 34 | 355 | 0 | 190 | 0 | 1.00 | 545 |
| **7** | | 3859 | 0.09 | 333 | 179 | 0.19 | 34 | 368 | 0 | 190 | 0 | 1.00 | 558 |
| **8** | | 3859 | 0.09 | 346 | 179 | 0.20 | 35 | 381 | 0 | 190 | 0 | 1.00 | 571 |
| **9** | | 3859 | 0.09 | 359 | 179 | 0.20 | 36 | 395 | 0 | 190 | 0 | 1.00 | 585 |
| **10** | | 3859 | 0.10 | 373 | 179 | 0.21 | 37 | 409 | 196 | 190 | 0 | 0.97 | 773 |
| **11** | | 3859 | 0.10 | 387 | 179 | 0.21 | 38 | 424 | 0 | 190 | 0 | 0.97 | 596 |
| **12** | | 3859 | 0.10 | 401 | 179 | 0.21 | 38 | 440 | 0 | 190 | 0 | 0.97 | 609 |
| **13** | | 3859 | 0.11 | 417 | 179 | 0.22 | 39 | 456 | 0 | 190 | 0 | 0.96 | 623 |
| **14** | | 3859 | 0.11 | 432 | 179 | 0.22 | 40 | 473 | 0 | 190 | 0 | 0.96 | 637 |
| **15** | | 3859 | 0.12 | 449 | 179 | 0.23 | 41 | 490 | 196 | 190 | 0 | 0.92 | 806 |
| **16** | | 3859 | 0.12 | 466 | 179 | 0.23 | 42 | 508 | 0 | 190 | 0 | 0.92 | 639 |
| **17** | | 3859 | 0.13 | 484 | 179 | 0.24 | 43 | 527 | 0 | 190 | 0 | 0.91 | 653 |
| **18** | | 3859 | 0.13 | 502 | 179 | 0.24 | 44 | 546 | 0 | 190 | 0 | 0.91 | 667 |
| **19** | | 3859 | 0.14 | 521 | 179 | 0.25 | 45 | 566 | 0 | 190 | 0 | 0.90 | 681 |
| **20** | | 3859 | 0.14 | 541 | 179 | 0.26 | 46 | 587 | 196 | 190 | 0 | 0.85 | 822 |
| **21** | | 3859 | 0.15 | 561 | 179 | 0.26 | 47 | 608 | 0 | 190 | 0 | 0.84 | 669 |
| **22** | | 3859 | 0.15 | 583 | 179 | 0.27 | 48 | 631 | 0 | 190 | 0 | 0.83 | 682 |
| **23** | | 3859 | 0.16 | 605 | 179 | 0.27 | 49 | 654 | 0 | 190 | 0 | 0.82 | 696 |
| **24** | | 3859 | 0.16 | 628 | 179 | 0.28 | 50 | 678 | 0 | 190 | 0 | 0.82 | 710 |
| **25** | | 3859 | 0.17 | 652 | 179 | 0.28 | 51 | 703 | 1120 | 190 | 0 | 0.80 | 1609 |
| **26** | | 3859 | 0.18 | 677 | 179 | 0.29 | 52 | 729 | 0 | 190 | 0 | 0.79 | 728 |
| **27** | | 3859 | 0.18 | 702 | 179 | 0.30 | 53 | 756 | 0 | 190 | 0 | 0.79 | 742 |
| **28** | | 3859 | 0.19 | 729 | 179 | 0.30 | 54 | 783 | 0 | 190 | 0 | 0.78 | 757 |
| **29** | | 3859 | 0.20 | 757 | 179 | 0.31 | 56 | 812 | 0 | 190 | 0 | 0.77 | 773 |
| **30** | | 3859 | 0.20 | 785 | 179 | 0 | 57 | 842 | 0 | 190 | 0 | 0.76 | 789 |
| **Total** | | 115,784 | 4 | 14,446 | 5,374 | 7 | 1,267 | 15,713 | 2,827 | 5,700 | 0 | 27 | 21,585 |

**LCCA of retrofit scenarios of the classroom in the first floor under the extended school curriculum during the afternoon (7:30-13:35, 14:45-17:45).**

| Case 1 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 1,391 | | | | | | | | | | | | 1,391 |
| **1** | | 3613 | 0.07 | 249 | 190 | 0.17 | 32 | 281 | 0 | 190 | 0 | 1.00 | 471 |
| **2** | | 3613 | 0.07 | 259 | 190 | 0.17 | 33 | 292 | 0 | 190 | 0 | 1.00 | 482 |
| **3** | | 3613 | 0.07 | 269 | 190 | 0.18 | 33 | 302 | 0 | 190 | 0 | 1.00 | 492 |
| **4** | | 3613 | 0.08 | 279 | 190 | 0.18 | 34 | 313 | 0 | 190 | 0 | 1.00 | 503 |
| **5** | | 3613 | 0.08 | 289 | 190 | 0.18 | 35 | 324 | 925 | 190 | 0 | 1.00 | 1439 |
| **6** | | 3613 | 0.08 | 300 | 190 | 0.19 | 36 | 336 | 0 | 190 | 0 | 1.00 | 526 |
| **7** | | 3613 | 0.09 | 312 | 190 | 0.19 | 37 | 348 | 0 | 190 | 0 | 1.00 | 538 |
| **8** | | 3613 | 0.09 | 324 | 190 | 0.20 | 37 | 361 | 0 | 190 | 0 | 1.00 | 551 |
| **9** | | 3613 | 0.09 | 336 | 190 | 0.20 | 38 | 374 | 0 | 190 | 0 | 1.00 | 564 |
| **10** | | 3613 | 0.10 | 349 | 190 | 0.21 | 39 | 388 | 0 | 190 | 0 | 0.97 | 562 |
| **11** | | 3613 | 0.10 | 362 | 190 | 0.21 | 40 | 402 | 0 | 190 | 0 | 0.97 | 574 |
| **12** | | 3613 | 0.10 | 376 | 190 | 0.21 | 41 | 417 | 0 | 190 | 0 | 0.97 | 587 |
| **13** | | 3613 | 0.11 | 390 | 190 | 0.22 | 42 | 432 | 0 | 190 | 0 | 0.96 | 600 |
| **14** | | 3613 | 0.11 | 405 | 190 | 0.22 | 43 | 447 | 0 | 190 | 0 | 0.96 | 613 |
| **15** | | 3613 | 0.12 | 420 | 190 | 0.23 | 43 | 464 | 196 | 190 | 0 | 0.92 | 782 |
| **16** | | 3613 | 0.12 | 436 | 190 | 0.23 | 44 | 481 | 0 | 190 | 0 | 0.92 | 614 |
| **17** | | 3613 | 0.13 | 453 | 190 | 0.24 | 45 | 498 | 0 | 190 | 0 | 0.91 | 627 |
| **18** | | 3613 | 0.13 | 470 | 190 | 0.24 | 46 | 516 | 0 | 190 | 0 | 0.91 | 640 |
| **19** | | 3613 | 0.14 | 488 | 190 | 0.25 | 47 | 535 | 0 | 190 | 0 | 0.90 | 654 |
| **20** | | 3613 | 0.14 | 506 | 190 | 0.26 | 48 | 555 | 0 | 190 | 0 | 0.85 | 630 |
| **21** | | 3613 | 0.15 | 526 | 190 | 0.26 | 50 | 575 | 0 | 190 | 0 | 0.84 | 642 |
| **22** | | 3613 | 0.15 | 546 | 190 | 0.27 | 51 | 596 | 0 | 190 | 0 | 0.83 | 654 |
| **23** | | 3613 | 0.16 | 566 | 190 | 0.27 | 52 | 618 | 0 | 190 | 0 | 0.82 | 666 |
| **24** | | 3613 | 0.16 | 588 | 190 | 0.28 | 53 | 641 | 0 | 190 | 0 | 0.82 | 679 |
| **25** | | 3613 | 0.17 | 610 | 190 | 0.28 | 54 | 664 | 925 | 190 | 0 | 0.80 | 1422 |
| **26** | | 3613 | 0.18 | 633 | 190 | 0.29 | 55 | 689 | 0 | 190 | 0 | 0.79 | 696 |
| **27** | | 3613 | 0.18 | 658 | 190 | 0.30 | 56 | 714 | 0 | 190 | 0 | 0.79 | 710 |
| **28** | | 3613 | 0.19 | 683 | 190 | 0.30 | 58 | 740 | 0 | 190 | 0 | 0.78 | 724 |
| **29** | | 3613 | 0.20 | 708 | 190 | 0.31 | 59 | 767 | 0 | 190 | 0 | 0.77 | 738 |
| **30** | | 3613 | 0.20 | 735 | 190 | 0.32 | 60 | 796 | 0 | 190 | 0 | 0.76 | 753 |
| **Total** | 1,391 | 108,404 | 4 | 13,526 | 5,696 | 7 | 1,343 | 14,868 | €2,045 | 5,700 | - | 27.24 | 21,524 |

| Case 2 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 1,521 | | | | | | | | | | | | 1,521 |
| **1** | | 3582 | 0.07 | 247 | 190 | 0.17 | 32 | 279 | 0 | 190 | 0 | 1.00 | 469 |
| **2** | | 3582 | 0.07 | 257 | 190 | 0.17 | 33 | 289 | 0 | 190 | 0 | 1.00 | 479 |
| **3** | | 3582 | 0.07 | 266 | 190 | 0.18 | 34 | 300 | 0 | 190 | 0 | 1.00 | 490 |
| **4** | | 3582 | 0.08 | 276 | 190 | 0.18 | 34 | 311 | 0 | 190 | 0 | 1.00 | 501 |
| **5** | | 3582 | 0.08 | 287 | 190 | 0.18 | 35 | 322 | 925 | 190 | 0 | 1.00 | 1437 |
| **6** | | 3582 | 0.08 | 298 | 190 | 0.19 | 36 | 334 | 0 | 190 | 0 | 1.00 | 524 |
| **7** | | 3582 | 0.09 | 309 | 190 | 0.19 | 37 | 346 | 0 | 190 | 0 | 1.00 | 536 |
| **8** | | 3582 | 0.09 | 321 | 190 | 0.20 | 37 | 358 | 0 | 190 | 0 | 1.00 | 548 |
| **9** | | 3582 | 0.09 | 333 | 190 | 0.20 | 38 | 371 | 0 | 190 | 0 | 1.00 | 561 |
| **10** | | 3582 | 0.10 | 346 | 190 | 0.21 | 39 | 385 | 0 | 190 | 0 | 0.97 | 559 |
| **11** | | 3582 | 0.10 | 359 | 190 | 0.21 | 40 | 399 | 0 | 190 | 0 | 0.97 | 571 |
| **12** | | 3582 | 0.10 | 373 | 190 | 0.21 | 41 | 413 | 0 | 190 | 0 | 0.97 | 583 |
| **13** | | 3582 | 0.11 | 387 | 190 | 0.22 | 42 | 428 | 0 | 190 | 0 | 0.96 | 596 |
| **14** | | 3582 | 0.11 | 401 | 190 | 0.22 | 43 | 444 | 0 | 190 | 0 | 0.96 | 610 |
| **15** | | 3582 | 0.12 | 417 | 190 | 0.23 | 44 | 460 | 196 | 190 | 0 | 0.92 | 779 |
| **16** | | 3582 | 0.12 | 432 | 190 | 0.23 | 45 | 477 | 0 | 190 | 0 | 0.92 | 611 |
| **17** | | 3582 | 0.13 | 449 | 190 | 0.24 | 46 | 494 | 0 | 190 | 0 | 0.91 | 624 |
| **18** | | 3582 | 0.13 | 466 | 190 | 0.24 | 47 | 513 | 0 | 190 | 0 | 0.91 | 636 |
| **19** | | 3582 | 0.14 | 484 | 190 | 0.25 | 48 | 531 | 0 | 190 | 0 | 0.90 | 650 |
| **20** | | 3582 | 0.14 | 502 | 190 | 0.26 | 49 | 551 | 0 | 190 | 0 | 0.85 | 626 |
| **21** | | 3582 | 0.15 | 521 | 190 | 0.26 | 50 | 571 | 0 | 190 | 0 | 0.84 | 638 |
| **22** | | 3582 | 0.15 | 541 | 190 | 0.27 | 51 | 592 | 0 | 190 | 0 | 0.83 | 650 |
| **23** | | 3582 | 0.16 | 561 | 190 | 0.27 | 52 | 613 | 0 | 190 | 0 | 0.82 | 662 |
| **24** | | 3582 | 0.16 | 583 | 190 | 0.28 | 53 | 636 | 0 | 190 | 0 | 0.82 | 675 |
| **25** | | 3582 | 0.17 | 605 | 190 | 0.28 | 54 | 659 | 925 | 190 | 0 | 0.80 | 1418 |
| **26** | | 3582 | 0.18 | 628 | 190 | 0.29 | 55 | 683 | 0 | 190 | 0 | 0.79 | 692 |
| **27** | | 3582 | 0.18 | 652 | 190 | 0.30 | 57 | 708 | 0 | 190 | 0 | 0.79 | 705 |
| **28** | | 3582 | 0.19 | 677 | 190 | 0.30 | 58 | 734 | 0 | 190 | 0 | 0.78 | 719 |
| **29** | | 3582 | 0.20 | 702 | 190 | 0.31 | 59 | 761 | 0 | 190 | 0 | 0.77 | 734 |
| **30** | | 3582 | 0.20 | 729 | 190 | 0.32 | 60 | 789 | 0 | 190 | 0 | 0.76 | 749 |
| **Total** | 1,521 | 107,462 | 4 | 13,408 | 5,712 | 7 | 1,346 | 14,754 | 2,045 | 5,700 | - | 28 | 21,554 |

**Case 3**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,619 | | | | | | | | | | | | 1,619 |
| **1** | | 3570 | 0.07 | 246 | 191 | 0.17 | 32 | 279 | 0 | 190 | 0 | 1.00 | 469 |
| **2** | | 3570 | 0.07 | 256 | 191 | 0.17 | 33 | 289 | 0 | 190 | 0 | 1.00 | 479 |
| **3** | | 3570 | 0.07 | 265 | 191 | 0.18 | 34 | 299 | 0 | 190 | 0 | 1.00 | 489 |
| **4** | | 3570 | 0.08 | 275 | 191 | 0.18 | 34 | 310 | 0 | 190 | 0 | 1.00 | 500 |
| **5** | | 3570 | 0.08 | 286 | 191 | 0.18 | 35 | 321 | 925 | 190 | 0 | 1.00 | 1436 |
| **6** | | 3570 | 0.08 | 297 | 191 | 0.19 | 36 | 333 | 0 | 190 | 0 | 1.00 | 523 |
| **7** | | 3570 | 0.09 | 308 | 191 | 0.19 | 37 | 345 | 0 | 190 | 0 | 1.00 | 535 |
| **8** | | 3570 | 0.09 | 320 | 191 | 0.20 | 37 | 357 | 0 | 190 | 0 | 1.00 | 547 |
| **9** | | 3570 | 0.09 | 332 | 191 | 0.20 | 38 | 370 | 0 | 190 | 0 | 1.00 | 560 |
| **10** | | 3570 | 0.10 | 345 | 191 | 0.21 | 39 | 384 | 0 | 190 | 0 | 0.97 | 558 |
| **11** | | 3570 | 0.10 | 358 | 191 | 0.21 | 40 | 398 | 0 | 190 | 0 | 0.97 | 570 |
| **12** | | 3570 | 0.10 | 371 | 191 | 0.21 | 41 | 412 | 0 | 190 | 0 | 0.97 | 582 |
| **13** | | 3570 | 0.11 | 385 | 191 | 0.22 | 42 | 427 | 0 | 190 | 0 | 0.96 | 595 |
| **14** | | 3570 | 0.11 | 400 | 191 | 0.22 | 43 | 443 | 0 | 190 | 0 | 0.96 | 608 |
| **15** | | 3570 | 0.12 | 415 | 191 | 0.23 | 44 | 459 | 196 | 190 | 0 | 0.92 | 778 |
| **16** | | 3570 | 0.12 | 431 | 191 | 0.23 | 45 | 476 | 0 | 190 | 0 | 0.92 | 610 |
| **17** | | 3570 | 0.13 | 447 | 191 | 0.24 | 46 | 493 | 0 | 190 | 0 | 0.91 | 622 |
| **18** | | 3570 | 0.13 | 464 | 191 | 0.24 | 47 | 511 | 0 | 190 | 0 | 0.91 | 635 |
| **19** | | 3570 | 0.14 | 482 | 191 | 0.25 | 48 | 530 | 0 | 190 | 0 | 0.90 | 648 |
| **20** | | 3570 | 0.14 | 500 | 191 | 0.26 | 49 | 549 | 0 | 190 | 0 | 0.85 | 625 |
| **21** | | 3570 | 0.15 | 519 | 191 | 0.26 | 50 | 569 | 0 | 190 | 0 | 0.84 | 637 |
| **22** | | 3570 | 0.15 | 539 | 191 | 0.27 | 51 | 590 | 0 | 190 | 0 | 0.83 | 649 |
| **23** | | 3570 | 0.16 | 560 | 191 | 0.27 | 52 | 612 | 0 | 190 | 0 | 0.82 | 661 |
| **24** | | 3570 | 0.16 | 581 | 191 | 0.28 | 53 | 634 | 0 | 190 | 0 | 0.82 | 674 |
| **25** | | 3570 | 0.17 | 603 | 191 | 0.28 | 54 | 657 | 925 | 190 | 0 | 0.80 | 1416 |
| **26** | | 3570 | 0.18 | 626 | 191 | 0.29 | 55 | 681 | 0 | 190 | 0 | 0.79 | 690 |
| **27** | | 3570 | 0.18 | 650 | 191 | 0.30 | 57 | 706 | 0 | 190 | 0 | 0.79 | 704 |
| **28** | | 3570 | 0.19 | 674 | 191 | 0.30 | 58 | 732 | 0 | 190 | 0 | 0.78 | 718 |
| **29** | | 3570 | 0.20 | 700 | 191 | 0.31 | 59 | 759 | 0 | 190 | 0 | 0.77 | 732 |
| **30** | | 3570 | 0.20 | 726 | 191 | 0.32 | 61 | 787 | 0 | 190 | 0 | 0.76 | 747 |
| **Total** | 1,619 | 107,093 | 4 | 13,362 | 5,718 | 7 | 1,348 | 14,710 | 2,045 | 5,700 | - | 28 | 21,613 |

**Case 4**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,782 | | | | | | | | | | | | 1,782 |
| **1** | | 3551 | 0.07 | 245 | 191 | 0.17 | 32 | 277 | 0 | 190 | 0 | 1.00 | 467 |
| **2** | | 3551 | 0.07 | 254 | 191 | 0.17 | 33 | 287 | 0 | 190 | 0 | 1.00 | 477 |
| **3** | | 3551 | 0.07 | 264 | 191 | 0.18 | 34 | 298 | 0 | 190 | 0 | 1.00 | 488 |
| **4** | | 3551 | 0.08 | 274 | 191 | 0.18 | 34 | 308 | 0 | 190 | 0 | 1.00 | 498 |
| **5** | | 3551 | 0.08 | 284 | 191 | 0.18 | 35 | 320 | 925 | 190 | 0 | 1.00 | 1434 |
| **6** | | 3551 | 0.08 | 295 | 191 | 0.19 | 36 | 331 | 0 | 190 | 0 | 1.00 | 521 |
| **7** | | 3551 | 0.09 | 306 | 191 | 0.19 | 37 | 343 | 0 | 190 | 0 | 1.00 | 533 |
| **8** | | 3551 | 0.09 | 318 | 191 | 0.20 | 38 | 356 | 0 | 190 | 0 | 1.00 | 546 |
| **9** | | 3551 | 0.09 | 330 | 191 | 0.20 | 38 | 369 | 0 | 190 | 0 | 1.00 | 559 |
| **10** | | 3551 | 0.10 | 343 | 191 | 0.21 | 39 | 382 | 0 | 190 | 0 | 0.97 | 556 |
| **11** | | 3551 | 0.10 | 356 | 191 | 0.21 | 40 | 396 | 0 | 190 | 0 | 0.97 | 568 |
| **12** | | 3551 | 0.10 | 369 | 191 | 0.21 | 41 | 410 | 0 | 190 | 0 | 0.97 | 580 |
| **13** | | 3551 | 0.11 | 383 | 191 | 0.22 | 42 | 425 | 0 | 190 | 0 | 0.96 | 593 |
| **14** | | 3551 | 0.11 | 398 | 191 | 0.22 | 43 | 441 | 0 | 190 | 0 | 0.96 | 607 |
| **15** | | 3551 | 0.12 | 413 | 191 | 0.23 | 44 | 457 | 196 | 190 | 0 | 0.92 | 776 |
| **16** | | 3551 | 0.12 | 429 | 191 | 0.23 | 45 | 473 | 0 | 190 | 0 | 0.92 | 608 |
| **17** | | 3551 | 0.13 | 445 | 191 | 0.24 | 46 | 491 | 0 | 190 | 0 | 0.91 | 620 |
| **18** | | 3551 | 0.13 | 462 | 191 | 0.24 | 47 | 509 | 0 | 190 | 0 | 0.91 | 633 |
| **19** | | 3551 | 0.14 | 480 | 191 | 0.25 | 48 | 527 | 0 | 190 | 0 | 0.90 | 646 |
| **20** | | 3551 | 0.14 | 498 | 191 | 0.26 | 49 | 546 | 0 | 190 | 0 | 0.85 | 623 |
| **21** | | 3551 | 0.15 | 517 | 191 | 0.26 | 50 | 566 | 0 | 190 | 0 | 0.84 | 634 |
| **22** | | 3551 | 0.15 | 536 | 191 | 0.27 | 51 | 587 | 0 | 190 | 0 | 0.83 | 646 |
| **23** | | 3551 | 0.16 | 557 | 191 | 0.27 | 52 | 609 | 0 | 190 | 0 | 0.82 | 659 |
| **24** | | 3551 | 0.16 | 578 | 191 | 0.28 | 53 | 631 | 0 | 190 | 0 | 0.82 | 671 |
| **25** | | 3551 | 0.17 | 600 | 191 | 0.28 | 54 | 654 | 925 | 190 | 0 | 0.80 | 1414 |
| **26** | | 3551 | 0.18 | 623 | 191 | 0.29 | 56 | 678 | 0 | 190 | 0 | 0.79 | 688 |
| **27** | | 3551 | 0.18 | 646 | 191 | 0.30 | 57 | 703 | 0 | 190 | 0 | 0.79 | 701 |
| **28** | | 3551 | 0.19 | 671 | 191 | 0.30 | 58 | 729 | 0 | 190 | 0 | 0.78 | 715 |
| **29** | | 3551 | 0.20 | 696 | 191 | 0.31 | 59 | 756 | 0 | 190 | 0 | 0.77 | 729 |
| **30** | | 3551 | 0.20 | 723 | 191 | 0.32 | 61 | 783 | 0 | 190 | 0 | 0.76 | 744 |
| **Total** | 1,782 | 106,539 | 4 | 13,293 | 5,727 | 7 | 1,350 | 14,643 | 2,045 | 5,700 | - | 28 | 21,717 |

| Case 5 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 3,024 | | | | | | | | | | | | 3,024 |
| **1** | | 3236 | 0.07 | 223 | 123 | 0.17 | 21 | 244 | 0 | 190 | 0 | 1.00 | 434 |
| **2** | | 3236 | 0.07 | 232 | 123 | 0.17 | 21 | 253 | 0 | 190 | 0 | 1.00 | 443 |
| **3** | | 3236 | 0.07 | 241 | 123 | 0.18 | 22 | 262 | 0 | 190 | 0 | 1.00 | 452 |
| **4** | | 3236 | 0.08 | 250 | 123 | 0.18 | 22 | 272 | 0 | 190 | 0 | 1.00 | 462 |
| **5** | | 3236 | 0.08 | 259 | 123 | 0.18 | 23 | 282 | 196 | 190 | 0 | 1.00 | 668 |
| **6** | | 3236 | 0.08 | 269 | 123 | 0.19 | 23 | 292 | 0 | 190 | 0 | 1.00 | 482 |
| **7** | | 3236 | 0.09 | 279 | 123 | 0.19 | 24 | 303 | 0 | 190 | 0 | 1.00 | 493 |
| **8** | | 3236 | 0.09 | 290 | 123 | 0.20 | 24 | 314 | 0 | 190 | 0 | 1.00 | 504 |
| **9** | | 3236 | 0.09 | 301 | 123 | 0.20 | 25 | 326 | 0 | 190 | 0 | 1.00 | 516 |
| **10** | | 3236 | 0.10 | 312 | 123 | 0.21 | 25 | 338 | 196 | 190 | 0 | 0.97 | 703 |
| **11** | | 3236 | 0.10 | 324 | 123 | 0.21 | 26 | 350 | 0 | 190 | 0 | 0.97 | 524 |
| **12** | | 3236 | 0.10 | 337 | 123 | 0.21 | 26 | 363 | 0 | 190 | 0 | 0.97 | 535 |
| **13** | | 3236 | 0.11 | 349 | 123 | 0.22 | 27 | 376 | 0 | 190 | 0 | 0.96 | 546 |
| **14** | | 3236 | 0.11 | 363 | 123 | 0.22 | 28 | 390 | 0 | 190 | 0 | 0.96 | 558 |
| **15** | | 3236 | 0.12 | 376 | 123 | 0.23 | 28 | 405 | 196 | 190 | 0 | 0.92 | 728 |
| **16** | | 3236 | 0.12 | 391 | 123 | 0.23 | 29 | 420 | 0 | 190 | 0 | 0.92 | 558 |
| **17** | | 3236 | 0.13 | 406 | 123 | 0.24 | 30 | 435 | 0 | 190 | 0 | 0.91 | 569 |
| **18** | | 3236 | 0.13 | 421 | 123 | 0.24 | 30 | 451 | 0 | 190 | 0 | 0.91 | 581 |
| **19** | | 3236 | 0.14 | 437 | 123 | 0.25 | 31 | 468 | 0 | 190 | 0 | 0.90 | 593 |
| **20** | | 3236 | 0.14 | 454 | 123 | 0.26 | 32 | 485 | 196 | 190 | 0 | 0.85 | 736 |
| **21** | | 3236 | 0.15 | 471 | 123 | 0.26 | 32 | 503 | 0 | 190 | 0 | 0.84 | 581 |
| **22** | | 3236 | 0.15 | 489 | 123 | 0.27 | 33 | 522 | 0 | 190 | 0 | 0.83 | 592 |
| **23** | | 3236 | 0.16 | 507 | 123 | 0.27 | 34 | 541 | 0 | 190 | 0 | 0.82 | 603 |
| **24** | | 3236 | 0.16 | 527 | 123 | 0.28 | 34 | 561 | 0 | 190 | 0 | 0.82 | 614 |
| **25** | | 3236 | 0.17 | 547 | 123 | 0.28 | 35 | 582 | 196 | 190 | 0 | 0.80 | 773 |
| **26** | | 3236 | 0.18 | 567 | 123 | 0.29 | 36 | 603 | 0 | 190 | 0 | 0.79 | 628 |
| **27** | | 3236 | 0.18 | 589 | 123 | 0.30 | 37 | 626 | 0 | 190 | 0 | 0.79 | 640 |
| **28** | | 3236 | 0.19 | 611 | 123 | 0.30 | 38 | 649 | 0 | 190 | 0 | 0.78 | 653 |
| **29** | | 3236 | 0.20 | 634 | 123 | 0.31 | 38 | 673 | 0 | 190 | 0 | 0.77 | 665 |
| **30** | | 3236 | 0.20 | 659 | 123 | 0.32 | 39 | 698 | 0 | 190 | 150 | 0.76 | 564 |
| **Total** | 3,024 | 97,086 | 4 | 12,113 | 3,701 | 7 | 872 | 12,986 | 978 | 5,700 | 150 | 28 | 20,423 |

| Case 6 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 3,444 | | | | | | | | | | | | 3,444 |
| **1** | | 3164 | 0.07 | 218 | 115 | 0.17 | 19 | 238 | 0 | 190 | 0 | 1.00 | 408 |
| **2** | | 3164 | 0.07 | 227 | 115 | 0.17 | 20 | 247 | | 190 | 0 | 1.00 | 437 |
| **3** | | 3164 | 0.07 | 235 | 115 | 0.18 | 20 | 256 | | 190 | 0 | 1.00 | 446 |
| **4** | | 3164 | 0.08 | 244 | 115 | 0.18 | 21 | 265 | | 190 | 0 | 1.00 | 455 |
| **5** | | 3164 | 0.08 | 253 | 115 | 0.18 | 21 | 275 | 196 | 190 | 0 | 1.00 | 660 |
| **6** | | 3164 | 0.08 | 263 | 115 | 0.19 | 22 | 285 | | 190 | 0 | 1.00 | 475 |
| **7** | | 3164 | 0.09 | 273 | 115 | 0.19 | 22 | 295 | | 190 | 0 | 1.00 | 485 |
| **8** | | 3164 | 0.09 | 283 | 115 | 0.20 | 23 | 306 | | 190 | 0 | 1.00 | 496 |
| **9** | | 3164 | 0.09 | 294 | 115 | 0.20 | 23 | 317 | | 190 | 0 | 1.00 | 507 |
| **10** | | 3164 | 0.10 | 305 | 115 | 0.21 | 24 | 329 | 196 | 190 | 0 | 0.97 | 695 |
| **11** | | 3164 | 0.10 | 317 | 115 | 0.21 | 24 | 341 | | 190 | 0 | 0.97 | 515 |
| **12** | | 3164 | 0.10 | 329 | 115 | 0.21 | 25 | 354 | | 190 | 0 | 0.97 | 526 |
| **13** | | 3164 | 0.11 | 342 | 115 | 0.22 | 25 | 367 | | 190 | 0 | 0.96 | 537 |
| **14** | | 3164 | 0.11 | 355 | 115 | 0.22 | 26 | 380 | | 190 | 0 | 0.96 | 548 |
| **15** | | 3164 | 0.12 | 368 | 115 | 0.23 | 26 | 394 | 196 | 190 | 0 | 0.92 | 718 |
| **16** | | 3164 | 0.12 | 382 | 115 | 0.23 | 27 | 409 | | 190 | 0 | 0.92 | 549 |
| **17** | | 3164 | 0.13 | 396 | 115 | 0.24 | 28 | 424 | | 190 | 0 | 0.91 | 559 |
| **18** | | 3164 | 0.13 | 412 | 115 | 0.24 | 28 | 440 | | 190 | 0 | 0.91 | 571 |
| **19** | | 3164 | 0.14 | 427 | 115 | 0.25 | 29 | 456 | | 190 | 0 | 0.90 | 582 |
| **20** | | 3164 | 0.14 | 443 | 115 | 0.26 | 29 | 473 | 196 | 190 | 0 | 0.85 | 726 |
| **21** | | 3164 | 0.15 | 460 | 115 | 0.26 | 30 | 490 | | 190 | 0 | 0.84 | 571 |
| **22** | | 3164 | 0.15 | 478 | 115 | 0.27 | 31 | 509 | | 190 | 0 | 0.83 | 581 |
| **23** | | 3164 | 0.16 | 496 | 115 | 0.27 | 31 | 527 | | 190 | 0 | 0.82 | 592 |
| **24** | | 3164 | 0.16 | 515 | 115 | 0.28 | 32 | 547 | | 190 | 0 | 0.82 | 603 |
| **25** | | 3164 | 0.17 | 534 | 115 | 0.28 | 33 | 567 | 196 | 190 | 0 | 0.80 | 762 |
| **26** | | 3164 | 0.18 | 555 | 115 | 0.29 | 34 | 588 | | 190 | 0 | 0.79 | 616 |
| **27** | | 3164 | 0.18 | 576 | 115 | 0.30 | 34 | 610 | | 190 | 0 | 0.79 | 628 |
| **28** | | 3164 | 0.19 | 598 | 115 | 0.30 | 35 | 633 | | 190 | 0 | 0.78 | 640 |
| **29** | | 3164 | 0.20 | 620 | 115 | 0.31 | 36 | 656 | | 190 | 0 | 0.77 | 653 |
| **30** | | 3164 | 0.20 | 644 | 115 | 0.32 | 37 | 680 | | 190 | 150 | 0.76 | 551 |
| **Total** | 3,444 | 94,914 | 4 | 11,842 | 3,462 | 7 | 816 | 12,658 | 978 | 5,700 | 150 | 28 | 20,535 |

**Case 7**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,864 | | | | | | | | | | | | 3,864 |
| **1** | | 3134 | 0.07 | 216 | 112 | 0.17 | 19 | 235 | 0 | 190 | 0 | 1.00 | 406 |
| **2** | | 3134 | 0.07 | 224 | 112 | 0.17 | 19 | 244 | 0 | 190 | 0 | 1.00 | 434 |
| **3** | | 3134 | 0.07 | 233 | 112 | 0.18 | 20 | 253 | 0 | 190 | 0 | 1.00 | 443 |
| **4** | | 3134 | 0.08 | 242 | 112 | 0.18 | 20 | 262 | 0 | 190 | 0 | 1.00 | 452 |
| **5** | | 3134 | 0.08 | 251 | 112 | 0.18 | 21 | 272 | 196 | 190 | 0 | 1.00 | 657 |
| **6** | | 3134 | 0.08 | 261 | 112 | 0.19 | 21 | 282 | 0 | 190 | 0 | 1.00 | 472 |
| **7** | | 3134 | 0.09 | 271 | 112 | 0.19 | 22 | 292 | 0 | 190 | 0 | 1.00 | 482 |
| **8** | | 3134 | 0.09 | 281 | 112 | 0.20 | 22 | 303 | 0 | 190 | 0 | 1.00 | 493 |
| **9** | | 3134 | 0.09 | 291 | 112 | 0.20 | 23 | 314 | 0 | 190 | 0 | 1.00 | 504 |
| **10** | | 3134 | 0.10 | 303 | 112 | 0.21 | 23 | 326 | 196 | 190 | 0 | 0.97 | 692 |
| **11** | | 3134 | 0.10 | 314 | 112 | 0.21 | 24 | 338 | 0 | 190 | 0 | 0.97 | 512 |
| **12** | | 3134 | 0.10 | 326 | 112 | 0.21 | 24 | 350 | 0 | 190 | 0 | 0.97 | 522 |
| **13** | | 3134 | 0.11 | 338 | 112 | 0.22 | 25 | 363 | 0 | 190 | 0 | 0.96 | 533 |
| **14** | | 3134 | 0.11 | 351 | 112 | 0.22 | 25 | 376 | 0 | 190 | 0 | 0.96 | 545 |
| **15** | | 3134 | 0.12 | 365 | 112 | 0.23 | 26 | 390 | 196 | 190 | 0 | 0.92 | 715 |
| **16** | | 3134 | 0.12 | 378 | 112 | 0.23 | 26 | 405 | 0 | 190 | 0 | 0.92 | 545 |
| **17** | | 3134 | 0.13 | 393 | 112 | 0.24 | 27 | 420 | 0 | 190 | 0 | 0.91 | 555 |
| **18** | | 3134 | 0.13 | 408 | 112 | 0.24 | 27 | 435 | 0 | 190 | 0 | 0.91 | 566 |
| **19** | | 3134 | 0.14 | 423 | 112 | 0.25 | 28 | 451 | 0 | 190 | 0 | 0.90 | 578 |
| **20** | | 3134 | 0.14 | 439 | 112 | 0.26 | 29 | 468 | 196 | 190 | 0 | 0.85 | 722 |
| **21** | | 3134 | 0.15 | 456 | 112 | 0.26 | 29 | 485 | 0 | 190 | 0 | 0.84 | 566 |
| **22** | | 3134 | 0.15 | 473 | 112 | 0.27 | 30 | 503 | 0 | 190 | 0 | 0.83 | 577 |
| **23** | | 3134 | 0.16 | 491 | 112 | 0.27 | 31 | 522 | 0 | 190 | 0 | 0.82 | 587 |
| **24** | | 3134 | 0.16 | 510 | 112 | 0.28 | 31 | 541 | 0 | 190 | 0 | 0.82 | 598 |
| **25** | | 3134 | 0.17 | 529 | 112 | 0.28 | 32 | 561 | 196 | 190 | 0 | 0.80 | 757 |
| **26** | | 3134 | 0.18 | 549 | 112 | 0.29 | 33 | 582 | 0 | 190 | 0 | 0.79 | 612 |
| **27** | | 3134 | 0.18 | 570 | 112 | 0.30 | 33 | 604 | 0 | 190 | 0 | 0.79 | 623 |
| **28** | | 3134 | 0.19 | 592 | 112 | 0.30 | 34 | 626 | 0 | 190 | 0 | 0.78 | 635 |
| **29** | | 3134 | 0.20 | 615 | 112 | 0.31 | 35 | 649 | 0 | 190 | 0 | 0.77 | 647 |
| **30** | | 3134 | 0.20 | 638 | 112 | 0.32 | 36 | 674 | 0 | 190 | 150 | 0.76 | 545 |
| **Total** | 3,864 | 94,030 | 3.74 | 11,732 | 3,372 | 7 | 795 | 12,527 | 978 | 5,700 | 150 | 28 | 20,839 |

**Case 8**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,284 | | | | | | | | | | | | 4,284 |
| **1** | | 3118 | 0.07 | 215 | 111 | 0.17 | 19 | 234 | 0 | 190 | 0 | 1.00 | 405 |
| **2** | | 3118 | 0.07 | 223 | 111 | 0.17 | 19 | 242 | 0 | 190 | 0 | 1.00 | 432 |
| **3** | | 3118 | 0.07 | 232 | 111 | 0.18 | 20 | 251 | 0 | 190 | 0 | 1.00 | 441 |
| **4** | | 3118 | 0.08 | 241 | 111 | 0.18 | 20 | 261 | 0 | 190 | 0 | 1.00 | 451 |
| **5** | | 3118 | 0.08 | 250 | 111 | 0.18 | 20 | 270 | 196 | 190 | 0 | 1.00 | 656 |
| **6** | | 3118 | 0.08 | 259 | 111 | 0.19 | 21 | 280 | 0 | 190 | 0 | 1.00 | 470 |
| **7** | | 3118 | 0.09 | 269 | 111 | 0.19 | 21 | 290 | 0 | 190 | 0 | 1.00 | 480 |
| **8** | | 3118 | 0.09 | 279 | 111 | 0.20 | 22 | 301 | 0 | 190 | 0 | 1.00 | 491 |
| **9** | | 3118 | 0.09 | 290 | 111 | 0.20 | 22 | 312 | 0 | 190 | 0 | 1.00 | 502 |
| **10** | | 3118 | 0.10 | 301 | 111 | 0.21 | 23 | 324 | 196 | 190 | 0 | 0.97 | 690 |
| **11** | | 3118 | 0.10 | 312 | 111 | 0.21 | 23 | 336 | 0 | 190 | 0 | 0.97 | 510 |
| **12** | | 3118 | 0.10 | 324 | 111 | 0.21 | 24 | 348 | 0 | 190 | 0 | 0.97 | 520 |
| **13** | | 3118 | 0.11 | 337 | 111 | 0.22 | 24 | 361 | 0 | 190 | 0 | 0.96 | 531 |
| **14** | | 3118 | 0.11 | 349 | 111 | 0.22 | 25 | 374 | 0 | 190 | 0 | 0.96 | 543 |
| **15** | | 3118 | 0.12 | 363 | 111 | 0.23 | 25 | 388 | 196 | 190 | 0 | 0.92 | 713 |
| **16** | | 3118 | 0.12 | 376 | 111 | 0.23 | 26 | 402 | 0 | 190 | 0 | 0.92 | 543 |
| **17** | | 3118 | 0.13 | 391 | 111 | 0.24 | 27 | 417 | 0 | 190 | 0 | 0.91 | 553 |
| **18** | | 3118 | 0.13 | 406 | 111 | 0.24 | 27 | 433 | 0 | 190 | 0 | 0.91 | 564 |
| **19** | | 3118 | 0.14 | 421 | 111 | 0.25 | 28 | 449 | 0 | 190 | 0 | 0.90 | 575 |
| **20** | | 3118 | 0.14 | 437 | 111 | 0.26 | 28 | 465 | 196 | 190 | 0 | 0.85 | 720 |
| **21** | | 3118 | 0.15 | 454 | 111 | 0.26 | 29 | 483 | 0 | 190 | 0 | 0.84 | 564 |
| **22** | | 3118 | 0.15 | 471 | 111 | 0.27 | 30 | 500 | 0 | 190 | 0 | 0.83 | 574 |
| **23** | | 3118 | 0.16 | 489 | 111 | 0.27 | 30 | 519 | 0 | 190 | 0 | 0.82 | 585 |
| **24** | | 3118 | 0.16 | 507 | 111 | 0.28 | 31 | 538 | 0 | 190 | 0 | 0.82 | 595 |
| **25** | | 3118 | 0.17 | 527 | 111 | 0.28 | 32 | 558 | 196 | 190 | 0 | 0.80 | 754 |
| **26** | | 3118 | 0.18 | 547 | 111 | 0.29 | 32 | 579 | 0 | 190 | 0 | 0.79 | 609 |
| **27** | | 3118 | 0.18 | 567 | 111 | 0.30 | 33 | 600 | 0 | 190 | 0 | 0.79 | 621 |
| **28** | | 3118 | 0.19 | 589 | 111 | 0.30 | 34 | 623 | 0 | 190 | 0 | 0.78 | 632 |
| **29** | | 3118 | 0.20 | 611 | 111 | 0.31 | 34 | 646 | 0 | 190 | 0 | 0.77 | 645 |
| **30** | | 3118 | 0.20 | 635 | 111 | 0.32 | 35 | 670 | 0 | 190 | 150 | 0.76 | 542 |
| **Total** | 4,284 | 93,541 | 4 | 11,671 | 3,326 | 7 | 784 | 12,455 | 978 | 5,700 | 150 | 28 | 21,196 |

**Case 9**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,808 | | | | | | | | | | | | 3,808 |
| **1** | | 3696 | 0.07 | 255 | 191 | 0.17 | 32 | 287 | 0 | 190 | 0 | 1.00 | 445 |
| **2** | | 3696 | 0.07 | 265 | 191 | 0.17 | 33 | 298 | 0 | 190 | 0 | 1.00 | 488 |
| **3** | | 3696 | 0.07 | 275 | 191 | 0.18 | 34 | 308 | 0 | 190 | 0 | 1.00 | 498 |
| **4** | | 3696 | 0.08 | 285 | 191 | 0.18 | 34 | 320 | 0 | 190 | 0 | 1.00 | 510 |
| **5** | | 3696 | 0.08 | 296 | 191 | 0.18 | 35 | 331 | 1120 | 190 | 0 | 1.00 | 1641 |
| **6** | | 3696 | 0.08 | 307 | 191 | 0.19 | 36 | 343 | 0 | 190 | 0 | 1.00 | 533 |
| **7** | | 3696 | 0.09 | 319 | 191 | 0.19 | 37 | 356 | 0 | 190 | 0 | 1.00 | 546 |
| **8** | | 3696 | 0.09 | 331 | 191 | 0.20 | 38 | 369 | 0 | 190 | 0 | 1.00 | 559 |
| **9** | | 3696 | 0.09 | 344 | 191 | 0.20 | 38 | 382 | 0 | 190 | 0 | 1.00 | 572 |
| **10** | | 3696 | 0.10 | 357 | 191 | 0.21 | 39 | 396 | 196 | 190 | 0 | 0.97 | 760 |
| **11** | | 3696 | 0.10 | 370 | 191 | 0.21 | 40 | 410 | 0 | 190 | 0 | 0.97 | 582 |
| **12** | | 3696 | 0.10 | 384 | 191 | 0.21 | 41 | 425 | 0 | 190 | 0 | 0.97 | 595 |
| **13** | | 3696 | 0.11 | 399 | 191 | 0.22 | 42 | 441 | 0 | 190 | 0 | 0.96 | 608 |
| **14** | | 3696 | 0.11 | 414 | 191 | 0.22 | 43 | 457 | 0 | 190 | 0 | 0.96 | 622 |
| **15** | | 3696 | 0.12 | 430 | 191 | 0.23 | 44 | 474 | 196 | 190 | 0 | 0.92 | 791 |
| **16** | | 3696 | 0.12 | 446 | 191 | 0.23 | 45 | 491 | 0 | 190 | 0 | 0.92 | 624 |
| **17** | | 3696 | 0.13 | 463 | 191 | 0.24 | 46 | 509 | 0 | 190 | 0 | 0.91 | 637 |
| **18** | | 3696 | 0.13 | 481 | 191 | 0.24 | 47 | 527 | 0 | 190 | 0 | 0.91 | 650 |
| **19** | | 3696 | 0.14 | 499 | 191 | 0.25 | 48 | 547 | 0 | 190 | 0 | 0.90 | 664 |
| **20** | | 3696 | 0.14 | 518 | 191 | 0.26 | 49 | 567 | 196 | 190 | 0 | 0.85 | 805 |
| **21** | | 3696 | 0.15 | 538 | 191 | 0.26 | 50 | 588 | 0 | 190 | 0 | 0.84 | 652 |
| **22** | | 3696 | 0.15 | 558 | 191 | 0.27 | 51 | 609 | 0 | 190 | 0 | 0.83 | 664 |
| **23** | | 3696 | 0.16 | 579 | 191 | 0.27 | 52 | 631 | 0 | 190 | 0 | 0.82 | 677 |
| **24** | | 3696 | 0.16 | 601 | 191 | 0.28 | 53 | 655 | 0 | 190 | 0 | 0.82 | 691 |
| **25** | | 3696 | 0.17 | 624 | 191 | 0.28 | 54 | 679 | 1120 | 190 | 0 | 0.80 | 1590 |
| **26** | | 3696 | 0.18 | 648 | 191 | 0.29 | 56 | 704 | 0 | 190 | 0 | 0.79 | 708 |
| **27** | | 3696 | 0.18 | 673 | 191 | 0.30 | 57 | 729 | 0 | 190 | 0 | 0.79 | 722 |
| **28** | | 3696 | 0.19 | 698 | 191 | 0.30 | 58 | 756 | 0 | 190 | 0 | 0.78 | 736 |
| **29** | | 3696 | 0.20 | 725 | 191 | 0.31 | 59 | 784 | 0 | 190 | 0 | 0.77 | 751 |
| **30** | | 3696 | 0.20 | 752 | 191 | 0.32 | 61 | 813 | 0 | 190 | 0 | 0.76 | 766 |
| **Total** | 3,808 | 110,889 | 4 | 13,836 | 5,726 | 7 | 1,350 | 15,185 | 2,827 | 5,700 | - | 28 | 24,896 |

**Case 10**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,920 | | | | | | | | | | | | 3,920 |
| **1** | | 3679 | 0.07 | 254 | 192 | 0.17 | 32 | 286 | 0 | 190 | 0 | 1.00 | 444 |
| **2** | | 3679 | 0.07 | 264 | 192 | 0.17 | 33 | 297 | 0 | 190 | 0 | 1.00 | 487 |
| **3** | | 3679 | 0.07 | 274 | 192 | 0.18 | 34 | 307 | 0 | 190 | 0 | 1.00 | 497 |
| **4** | | 3679 | 0.08 | 284 | 192 | 0.18 | 35 | 318 | 0 | 190 | 0 | 1.00 | 508 |
| **5** | | 3679 | 0.08 | 295 | 192 | 0.18 | 35 | 330 | 1120 | 190 | 0 | 1.00 | 1640 |
| **6** | | 3679 | 0.08 | 306 | 192 | 0.19 | 36 | 342 | 0 | 190 | 0 | 1.00 | 532 |
| **7** | | 3679 | 0.09 | 318 | 192 | 0.19 | 37 | 354 | 0 | 190 | 0 | 1.00 | 544 |
| **8** | | 3679 | 0.09 | 330 | 192 | 0.20 | 38 | 367 | 0 | 190 | 0 | 1.00 | 557 |
| **9** | | 3679 | 0.09 | 342 | 192 | 0.20 | 39 | 381 | 0 | 190 | 0 | 1.00 | 571 |
| **10** | | 3679 | 0.10 | 355 | 192 | 0.21 | 39 | 394 | 196 | 190 | 0 | 0.97 | 759 |
| **11** | | 3679 | 0.10 | 369 | 192 | 0.21 | 40 | 409 | 0 | 190 | 0 | 0.97 | 581 |
| **12** | | 3679 | 0.10 | 383 | 192 | 0.21 | 41 | 424 | 0 | 190 | 0 | 0.97 | 593 |
| **13** | | 3679 | 0.11 | 397 | 192 | 0.22 | 42 | 439 | 0 | 190 | 0 | 0.96 | 607 |
| **14** | | 3679 | 0.11 | 412 | 192 | 0.22 | 43 | 455 | 0 | 190 | 0 | 0.96 | 620 |
| **15** | | 3679 | 0.12 | 428 | 192 | 0.23 | 44 | 472 | 196 | 190 | 0 | 0.92 | 790 |
| **16** | | 3679 | 0.12 | 444 | 192 | 0.23 | 45 | 489 | 0 | 190 | 0 | 0.92 | 622 |
| **17** | | 3679 | 0.13 | 461 | 192 | 0.24 | 46 | 507 | 0 | 190 | 0 | 0.91 | 635 |
| **18** | | 3679 | 0.13 | 479 | 192 | 0.24 | 47 | 525 | 0 | 190 | 0 | 0.91 | 648 |
| **19** | | 3679 | 0.14 | 497 | 192 | 0.25 | 48 | 545 | 0 | 190 | 0 | 0.90 | 662 |
| **20** | | 3679 | 0.14 | 516 | 192 | 0.26 | 49 | 565 | 196 | 190 | 0 | 0.85 | 803 |
| **21** | | 3679 | 0.15 | 535 | 192 | 0.26 | 50 | 585 | 0 | 190 | 0 | 0.84 | 650 |
| **22** | | 3679 | 0.15 | 556 | 192 | 0.27 | 51 | 607 | 0 | 190 | 0 | 0.83 | 662 |
| **23** | | 3679 | 0.16 | 577 | 192 | 0.27 | 52 | 629 | 0 | 190 | 0 | 0.82 | 675 |
| **24** | | 3679 | 0.16 | 599 | 192 | 0.28 | 53 | 652 | 0 | 190 | 0 | 0.82 | 688 |
| **25** | | 3679 | 0.17 | 621 | 192 | 0.28 | 55 | 676 | 1120 | 190 | 0 | 0.80 | 1587 |
| **26** | | 3679 | 0.18 | 645 | 192 | 0.29 | 56 | 701 | 0 | 190 | 0 | 0.79 | 706 |
| **27** | | 3679 | 0.18 | 669 | 192 | 0.30 | 57 | 726 | 0 | 190 | 0 | 0.79 | 720 |
| **28** | | 3679 | 0.19 | 695 | 192 | 0.30 | 58 | 753 | 0 | 190 | 0 | 0.78 | 734 |
| **29** | | 3679 | 0.20 | 721 | 192 | 0.31 | 60 | 781 | 0 | 190 | 0 | 0.77 | 749 |
| **30** | | 3679 | 0.20 | 749 | 192 | 0.32 | 61 | 810 | 0 | 190 | 0 | 0.76 | 764 |
| **Total** | 3,920 | 110,374 | 4 | 13,771 | 5,747 | 7 | 1,355 | 15,126 | 2,827 | 5,700 | - | 28 | 24,956 |

**Case 11**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,088 | | | | | | | | | | | | 4,088 |
| **1** | | 3672 | 0.07 | 253 | 192 | 0.17 | 32 | 286 | | 190 | 0 | 1.00 | 443 |
| **2** | | 3672 | 0.07 | 263 | 192 | 0.17 | 33 | 296 | | 190 | 0 | 1.00 | 486 |
| **3** | | 3672 | 0.07 | 273 | 192 | 0.18 | 34 | 307 | | 190 | 0 | 1.00 | 497 |
| **4** | | 3672 | 0.08 | 283 | 192 | 0.18 | 35 | 318 | | 190 | 0 | 1.00 | 508 |
| **5** | | 3672 | 0.08 | 294 | 192 | 0.18 | 35 | 329 | 1120 | 190 | 0 | 1.00 | 1640 |
| **6** | | 3672 | 0.08 | 305 | 192 | 0.19 | 36 | 341 | | 190 | 0 | 1.00 | 531 |
| **7** | | 3672 | 0.09 | 317 | 192 | 0.19 | 37 | 354 | | 190 | 0 | 1.00 | 544 |
| **8** | | 3672 | 0.09 | 329 | 192 | 0.20 | 38 | 367 | | 190 | 0 | 1.00 | 557 |
| **9** | | 3672 | 0.09 | 341 | 192 | 0.20 | 39 | 380 | | 190 | 0 | 1.00 | 570 |
| **10** | | 3672 | 0.10 | 354 | 192 | 0.21 | 39 | 394 | 196 | 190 | 0 | 0.97 | 758 |
| **11** | | 3672 | 0.10 | 368 | 192 | 0.21 | 40 | 408 | | 190 | 0 | 0.97 | 580 |
| **12** | | 3672 | 0.10 | 382 | 192 | 0.21 | 41 | 423 | | 190 | 0 | 0.97 | 593 |
| **13** | | 3672 | 0.11 | 396 | 192 | 0.22 | 42 | 438 | | 190 | 0 | 0.96 | 606 |
| **14** | | 3672 | 0.11 | 411 | 192 | 0.22 | 43 | 454 | | 190 | 0 | 0.96 | 620 |
| **15** | | 3672 | 0.12 | 427 | 192 | 0.23 | 44 | 471 | 196 | 190 | 0 | 0.92 | 789 |
| **16** | | 3672 | 0.12 | 443 | 192 | 0.23 | 45 | 488 | | 190 | 0 | 0.92 | 621 |
| **17** | | 3672 | 0.13 | 460 | 192 | 0.24 | 46 | 506 | | 190 | 0 | 0.91 | 634 |
| **18** | | 3672 | 0.13 | 478 | 192 | 0.24 | 47 | 525 | | 190 | 0 | 0.91 | 647 |
| **19** | | 3672 | 0.14 | 496 | 192 | 0.25 | 48 | 544 | | 190 | 0 | 0.90 | 661 |
| **20** | | 3672 | 0.14 | 515 | 192 | 0.26 | 49 | 564 | 196 | 190 | 0 | 0.85 | 803 |
| **21** | | 3672 | 0.15 | 534 | 192 | 0.26 | 50 | 584 | | 190 | 0 | 0.84 | 649 |
| **22** | | 3672 | 0.15 | 555 | 192 | 0.27 | 51 | 606 | | 190 | 0 | 0.83 | 662 |
| **23** | | 3672 | 0.16 | 576 | 192 | 0.27 | 52 | 628 | | 190 | 0 | 0.82 | 674 |
| **24** | | 3672 | 0.16 | 597 | 192 | 0.28 | 53 | 651 | | 190 | 0 | 0.82 | 688 |
| **25** | | 3672 | 0.17 | 620 | 192 | 0.28 | 55 | 675 | 1120 | 190 | 0 | 0.80 | 1587 |
| **26** | | 3672 | 0.18 | 644 | 192 | 0.29 | 56 | 700 | | 190 | 0 | 0.79 | 705 |
| **27** | | 3672 | 0.18 | 668 | 192 | 0.30 | 57 | 725 | | 190 | 0 | 0.79 | 719 |
| **28** | | 3672 | 0.19 | 694 | 192 | 0.30 | 58 | 752 | | 190 | 0 | 0.78 | 733 |
| **29** | | 3672 | 0.20 | 720 | 192 | 0.31 | 60 | 780 | | 190 | 0 | 0.77 | 748 |
| **30** | | 3672 | 0.20 | 747 | 192 | 0.32 | 61 | 808 | 0 | 190 | 0 | 0.76 | 763 |
| **Total** | 4,088 | 110,165 | 4 | 13,745 | 5,754 | 7 | 1,356 | 15,102 | 2,827 | 5,700 | - | 28 | 25,103 |

**Case 12**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 3,320 | | | | | | | | | | | | 3,320 |
| **1** | | 3886 | 0.07 | 268 | 178 | 0.17 | 30 | 298 | 0 | 140 | 0 | 1.00 | 408 |
| **2** | | 3886 | 0.07 | 278 | 178 | 0.17 | 31 | 309 | 0 | 140 | 0 | 1.00 | 449 |
| **3** | | 3886 | 0.07 | 289 | 178 | 0.18 | 31 | 320 | 0 | 140 | 0 | 1.00 | 460 |
| **4** | | 3886 | 0.08 | 300 | 178 | 0.18 | 32 | 332 | 0 | 140 | 0 | 1.00 | 472 |
| **5** | | 3886 | 0.08 | 311 | 178 | 0.18 | 33 | 344 | 1120 | 140 | 0 | 1.00 | 1604 |
| **6** | | 3886 | 0.08 | 323 | 178 | 0.19 | 34 | 357 | 0 | 140 | 0 | 1.00 | 497 |
| **7** | | 3886 | 0.09 | 335 | 178 | 0.19 | 34 | 370 | 0 | 140 | 0 | 1.00 | 510 |
| **8** | | 3886 | 0.09 | 348 | 178 | 0.20 | 35 | 383 | 0 | 140 | 0 | 1.00 | 523 |
| **9** | | 3886 | 0.09 | 361 | 178 | 0.20 | 36 | 397 | 0 | 140 | 0 | 1.00 | 537 |
| **10** | | 3886 | 0.10 | 375 | 178 | 0.21 | 37 | 412 | 196 | 140 | 0 | 0.97 | 727 |
| **11** | | 3886 | 0.10 | 389 | 178 | 0.21 | 37 | 427 | 0 | 140 | 0 | 0.97 | 550 |
| **12** | | 3886 | 0.10 | 404 | 178 | 0.21 | 38 | 442 | 0 | 140 | 0 | 0.97 | 563 |
| **13** | | 3886 | 0.11 | 419 | 178 | 0.22 | 39 | 459 | 0 | 140 | 0 | 0.96 | 577 |
| **14** | | 3886 | 0.11 | 435 | 178 | 0.22 | 40 | 475 | 0 | 140 | 0 | 0.96 | 592 |
| **15** | | 3886 | 0.12 | 452 | 178 | 0.23 | 41 | 493 | 196 | 140 | 0 | 0.92 | 763 |
| **16** | | 3886 | 0.12 | 469 | 178 | 0.23 | 42 | 511 | 0 | 140 | 0 | 0.92 | 596 |
| **17** | | 3886 | 0.13 | 487 | 178 | 0.24 | 43 | 530 | 0 | 140 | 0 | 0.91 | 610 |
| **18** | | 3886 | 0.13 | 505 | 178 | 0.24 | 44 | 549 | 0 | 140 | 0 | 0.91 | 624 |
| **19** | | 3886 | 0.14 | 525 | 178 | 0.25 | 45 | 569 | 0 | 140 | 0 | 0.90 | 639 |
| **20** | | 3886 | 0.14 | 545 | 178 | 0.26 | 46 | 590 | 196 | 140 | 0 | 0.85 | 783 |
| **21** | | 3886 | 0.15 | 565 | 178 | 0.26 | 47 | 612 | 0 | 140 | 0 | 0.84 | 630 |
| **22** | | 3886 | 0.15 | 587 | 178 | 0.27 | 48 | 634 | 0 | 140 | 0 | 0.83 | 644 |
| **23** | | 3886 | 0.16 | 609 | 178 | 0.27 | 49 | 658 | 0 | 140 | 0 | 0.82 | 658 |
| **24** | | 3886 | 0.16 | 632 | 178 | 0.28 | 50 | 682 | 0 | 140 | 0 | 0.82 | 672 |
| **25** | | 3886 | 0.17 | 656 | 178 | 0.28 | 51 | 707 | 1120 | 140 | 0 | 0.80 | 1572 |
| **26** | | 3886 | 0.18 | 681 | 178 | 0.29 | 52 | 733 | 0 | 140 | 0 | 0.79 | 692 |
| **27** | | 3886 | 0.18 | 707 | 178 | 0.30 | 53 | 760 | 0 | 140 | 0 | 0.79 | 707 |
| **28** | | 3886 | 0.19 | 734 | 178 | 0.30 | 54 | 788 | 0 | 140 | 0 | 0.78 | 722 |
| **29** | | 3886 | 0.20 | 762 | 178 | 0.31 | 55 | 817 | 0 | 140 | 0 | 0.77 | 738 |
| **30** | | 3886 | 0.20 | 791 | 178 | 0.32 | 57 | 847 | 0 | 140 | 0 | 0.76 | 755 |
| **Total** | 3,320 | 116,570 | 4 | 14,544 | 5,354 | 7 | 1,262 | 15,806 | 2,827 | 4,200 | - | 28 | 23,595 |

**Case 13**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,150 | | | | | | | | | | | | 4,150 |
| **1** | | 3880 | 0.07 | 268 | 175 | 0.17 | 29 | 297 | 0 | 140 | 0 | 1.00 | 408 |
| **2** | | 3880 | 0.07 | 278 | 175 | 0.17 | 30 | 308 | 0 | 140 | 0 | 1.00 | 448 |
| **3** | | 3880 | 0.07 | 288 | 175 | 0.18 | 31 | 319 | 0 | 140 | 0 | 1.00 | 459 |
| **4** | | 3880 | 0.08 | 299 | 175 | 0.18 | 31 | 331 | 0 | 140 | 0 | 1.00 | 471 |
| **5** | | 3880 | 0.08 | 311 | 175 | 0.18 | 32 | 343 | 1120 | 140 | 0 | 1.00 | 1603 |
| **6** | | 3880 | 0.08 | 323 | 175 | 0.19 | 33 | 355 | 0 | 140 | 0 | 1.00 | 495 |
| **7** | | 3880 | 0.09 | 335 | 175 | 0.19 | 34 | 368 | 0 | 140 | 0 | 1.00 | 508 |
| **8** | | 3880 | 0.09 | 348 | 175 | 0.20 | 34 | 382 | 0 | 140 | 0 | 1.00 | 522 |
| **9** | | 3880 | 0.09 | 361 | 175 | 0.20 | 35 | 396 | 0 | 140 | 0 | 1.00 | 536 |
| **10** | | 3880 | 0.10 | 374 | 175 | 0.21 | 36 | 410 | 196 | 140 | 0 | 0.97 | 725 |
| **11** | | 3880 | 0.10 | 389 | 175 | 0.21 | 37 | 425 | 0 | 140 | 0 | 0.97 | 548 |
| **12** | | 3880 | 0.10 | 403 | 175 | 0.21 | 37 | 441 | 0 | 140 | 0 | 0.97 | 562 |
| **13** | | 3880 | 0.11 | 419 | 175 | 0.22 | 38 | 457 | 0 | 140 | 0 | 0.96 | 576 |
| **14** | | 3880 | 0.11 | 435 | 175 | 0.22 | 39 | 474 | 0 | 140 | 0 | 0.96 | 590 |
| **15** | | 3880 | 0.12 | 451 | 175 | 0.23 | 40 | 491 | 196 | 140 | 0 | 0.92 | 762 |
| **16** | | 3880 | 0.12 | 468 | 175 | 0.23 | 41 | 509 | 0 | 140 | 0 | 0.92 | 595 |
| **17** | | 3880 | 0.13 | 486 | 175 | 0.24 | 42 | 528 | 0 | 140 | 0 | 0.91 | 609 |
| **18** | | 3880 | 0.13 | 505 | 175 | 0.24 | 43 | 547 | 0 | 140 | 0 | 0.91 | 623 |
| **19** | | 3880 | 0.14 | 524 | 175 | 0.25 | 44 | 567 | 0 | 140 | 0 | 0.90 | 637 |
| **20** | | 3880 | 0.14 | 544 | 175 | 0.26 | 45 | 588 | 196 | 140 | 0 | 0.85 | 781 |
| **21** | | 3880 | 0.15 | 564 | 175 | 0.26 | 46 | 610 | 0 | 140 | 0 | 0.84 | 629 |
| **22** | | 3880 | 0.15 | 586 | 175 | 0.27 | 47 | 632 | 0 | 140 | 0 | 0.83 | 642 |
| **23** | | 3880 | 0.16 | 608 | 175 | 0.27 | 48 | 656 | 0 | 140 | 0 | 0.82 | 656 |
| **24** | | 3880 | 0.16 | 631 | 175 | 0.28 | 49 | 680 | 0 | 140 | 0 | 0.82 | 670 |
| **25** | | 3880 | 0.17 | 655 | 175 | 0.28 | 50 | 705 | 1120 | 140 | 0 | 0.80 | 1571 |
| **26** | | 3880 | 0.18 | 680 | 175 | 0.29 | 51 | 731 | 0 | 140 | 0 | 0.79 | 690 |
| **27** | | 3880 | 0.18 | 706 | 175 | 0.30 | 52 | 758 | 0 | 140 | 0 | 0.79 | 705 |
| **28** | | 3880 | 0.19 | 733 | 175 | 0.30 | 53 | 786 | 0 | 140 | 0 | 0.78 | 720 |
| **29** | | 3880 | 0.20 | 761 | 175 | 0.31 | 54 | 815 | 0 | 140 | 0 | 0.77 | 736 |
| **30** | | 3880 | 0.20 | 790 | 175 | 0.32 | 55 | 845 | 0 | 140 | 0 | 0.76 | 753 |
| **Total** | 4,150 | 116,397 | 4 | 14,523 | 5,237 | 7 | 1,235 | 15,757 | 2,827 | 4,200 | - | 28 | 24,382 |

**Case 14**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,980 | | | | | | | | | | | | 4,980 |
| **1** | | 3860 | 0.07 | 266 | 174 | 0.17 | 29 | 296 | 0 | 140 | 0 | 1.00 | 406 |
| **2** | | 3860 | 0.07 | 276 | 174 | 0.17 | 30 | 306 | 0 | 140 | 0 | 1.00 | 446 |
| **3** | | 3860 | 0.07 | 287 | 174 | 0.18 | 31 | 318 | 0 | 140 | 0 | 1.00 | 458 |
| **4** | | 3860 | 0.08 | 298 | 174 | 0.18 | 31 | 329 | 0 | 140 | 0 | 1.00 | 469 |
| **5** | | 3860 | 0.08 | 309 | 174 | 0.18 | 32 | 341 | 1120 | 140 | 0 | 1.00 | 1601 |
| **6** | | 3860 | 0.08 | 321 | 174 | 0.19 | 33 | 354 | 0 | 140 | 0 | 1.00 | 494 |
| **7** | | 3860 | 0.09 | 333 | 174 | 0.19 | 33 | 367 | 0 | 140 | 0 | 1.00 | 507 |
| **8** | | 3860 | 0.09 | 346 | 174 | 0.20 | 34 | 380 | 0 | 140 | 0 | 1.00 | 520 |
| **9** | | 3860 | 0.09 | 359 | 174 | 0.20 | 35 | 394 | 0 | 140 | 0 | 1.00 | 534 |
| **10** | | 3860 | 0.10 | 373 | 174 | 0.21 | 36 | 408 | 196 | 140 | 0 | 0.97 | 723 |
| **11** | | 3860 | 0.10 | 387 | 174 | 0.21 | 37 | 423 | 0 | 140 | 0 | 0.97 | 546 |
| **12** | | 3860 | 0.10 | 401 | 174 | 0.21 | 37 | 439 | 0 | 140 | 0 | 0.97 | 560 |
| **13** | | 3860 | 0.11 | 417 | 174 | 0.22 | 38 | 455 | 0 | 140 | 0 | 0.96 | 574 |
| **14** | | 3860 | 0.11 | 433 | 174 | 0.22 | 39 | 471 | 0 | 140 | 0 | 0.96 | 588 |
| **15** | | 3860 | 0.12 | 449 | 174 | 0.23 | 40 | 489 | 196 | 140 | 0 | 0.92 | 759 |
| **16** | | 3860 | 0.12 | 466 | 174 | 0.23 | 41 | 507 | 0 | 140 | 0 | 0.92 | 592 |
| **17** | | 3860 | 0.13 | 484 | 174 | 0.24 | 42 | 525 | 0 | 140 | 0 | 0.91 | 606 |
| **18** | | 3860 | 0.13 | 502 | 174 | 0.24 | 43 | 545 | 0 | 140 | 0 | 0.91 | 620 |
| **19** | | 3860 | 0.14 | 521 | 174 | 0.25 | 43 | 565 | 0 | 140 | 0 | 0.90 | 635 |
| **20** | | 3860 | 0.14 | 541 | 174 | 0.26 | 44 | 585 | 196 | 140 | 0 | 0.85 | 779 |
| **21** | | 3860 | 0.15 | 562 | 174 | 0.26 | 45 | 607 | 0 | 140 | 0 | 0.84 | 626 |
| **22** | | 3860 | 0.15 | 583 | 174 | 0.27 | 46 | 629 | 0 | 140 | 0 | 0.83 | 640 |
| **23** | | 3860 | 0.16 | 605 | 174 | 0.27 | 47 | 652 | 0 | 140 | 0 | 0.82 | 653 |
| **24** | | 3860 | 0.16 | 628 | 174 | 0.28 | 48 | 676 | 0 | 140 | 0 | 0.82 | 668 |
| **25** | | 3860 | 0.17 | 652 | 174 | 0.28 | 50 | 701 | 1120 | 140 | 0 | 0.80 | 1568 |
| **26** | | 3860 | 0.18 | 677 | 174 | 0.29 | 51 | 727 | 0 | 140 | 0 | 0.79 | 687 |
| **27** | | 3860 | 0.18 | 702 | 174 | 0.30 | 52 | 754 | 0 | 140 | 0 | 0.79 | 702 |
| **28** | | 3860 | 0.19 | 729 | 174 | 0.30 | 53 | 782 | 0 | 140 | 0 | 0.78 | 717 |
| **29** | | 3860 | 0.20 | 757 | 174 | 0.31 | 54 | 811 | 0 | 140 | 0 | 0.77 | 733 |
| **30** | | 3860 | 0.20 | 786 | 174 | 0.32 | 55 | 841 | 0 | 140 | 0 | 0.76 | 750 |
| **Total** | 4,980 | 115,797 | 4 | 14,448 | 5,215 | 7 | 1,229 | 15,677 | 2,827 | 4,200 | - | 28 | 25,142 |

**Case 15**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 5,810 | | | | | | | | | | | | 5,810 |
| **1** | | 3876 | 0.07 | 267 | 171 | 0.17 | 29 | 296 | 0 | 140 | 0 | 1.00 | 407 |
| **2** | | 3876 | 0.07 | 278 | 171 | 0.17 | 30 | 307 | 0 | 140 | 0 | 1.00 | 447 |
| **3** | | 3876 | 0.07 | 288 | 171 | 0.18 | 30 | 318 | 0 | 140 | 0 | 1.00 | 458 |
| **4** | | 3876 | 0.08 | 299 | 171 | 0.18 | 31 | 330 | 0 | 140 | 0 | 1.00 | 470 |
| **5** | | 3876 | 0.08 | 311 | 171 | 0.18 | 32 | 342 | 1120 | 140 | 0 | 1.00 | 1602 |
| **6** | | 3876 | 0.08 | 322 | 171 | 0.19 | 32 | 355 | 0 | 140 | 0 | 1.00 | 495 |
| **7** | | 3876 | 0.09 | 335 | 171 | 0.19 | 33 | 368 | 0 | 140 | 0 | 1.00 | 508 |
| **8** | | 3876 | 0.09 | 347 | 171 | 0.20 | 34 | 381 | 0 | 140 | 0 | 1.00 | 521 |
| **9** | | 3876 | 0.09 | 360 | 171 | 0.20 | 34 | 395 | 0 | 140 | 0 | 1.00 | 535 |
| **10** | | 3876 | 0.10 | 374 | 171 | 0.21 | 35 | 409 | 196 | 140 | 0 | 0.97 | 724 |
| **11** | | 3876 | 0.10 | 388 | 171 | 0.21 | 36 | 424 | 0 | 140 | 0 | 0.97 | 547 |
| **12** | | 3876 | 0.10 | 403 | 171 | 0.21 | 37 | 440 | 0 | 140 | 0 | 0.97 | 561 |
| **13** | | 3876 | 0.11 | 418 | 171 | 0.22 | 38 | 456 | 0 | 140 | 0 | 0.96 | 575 |
| **14** | | 3876 | 0.11 | 434 | 171 | 0.22 | 38 | 473 | 0 | 140 | 0 | 0.96 | 589 |
| **15** | | 3876 | 0.12 | 451 | 171 | 0.23 | 39 | 490 | 196 | 140 | 0 | 0.92 | 760 |
| **16** | | 3876 | 0.12 | 468 | 171 | 0.23 | 40 | 508 | 0 | 140 | 0 | 0.92 | 594 |
| **17** | | 3876 | 0.13 | 486 | 171 | 0.24 | 41 | 527 | 0 | 140 | 0 | 0.91 | 607 |
| **18** | | 3876 | 0.13 | 504 | 171 | 0.24 | 42 | 546 | 0 | 140 | 0 | 0.91 | 622 |
| **19** | | 3876 | 0.14 | 523 | 171 | 0.25 | 43 | 566 | 0 | 140 | 0 | 0.90 | 636 |
| **20** | | 3876 | 0.14 | 543 | 171 | 0.26 | 44 | 587 | 196 | 140 | 0 | 0.85 | 780 |
| **21** | | 3876 | 0.15 | 564 | 171 | 0.26 | 45 | 609 | 0 | 140 | 0 | 0.84 | 628 |
| **22** | | 3876 | 0.15 | 585 | 171 | 0.27 | 46 | 631 | 0 | 140 | 0 | 0.83 | 641 |
| **23** | | 3876 | 0.16 | 608 | 171 | 0.27 | 47 | 654 | 0 | 140 | 0 | 0.82 | 655 |
| **24** | | 3876 | 0.16 | 631 | 171 | 0.28 | 48 | 678 | 0 | 140 | 0 | 0.82 | 669 |
| **25** | | 3876 | 0.17 | 655 | 171 | 0.28 | 49 | 703 | 1120 | 140 | 0 | 0.80 | 1570 |
| **26** | | 3876 | 0.18 | 680 | 171 | 0.29 | 50 | 729 | 0 | 140 | 0 | 0.79 | 689 |
| **27** | | 3876 | 0.18 | 705 | 171 | 0.30 | 51 | 756 | 0 | 140 | 0 | 0.79 | 704 |
| **28** | | 3876 | 0.19 | 732 | 171 | 0.30 | 52 | 784 | 0 | 140 | 0 | 0.78 | 719 |
| **29** | | 3876 | 0.20 | 760 | 171 | 0.31 | 53 | 813 | 0 | 140 | 0 | 0.77 | 735 |
| **30** | | 3876 | 0.20 | 789 | 171 | 0.32 | 54 | 843 | 0 | 140 | 0 | 0.76 | 751 |
| | | | | | | | | | | | | | 0.00 |
| **Total** | 5,810 | 116,292 | 4 | 14,510 | 5,136 | 7 | 1,211 | 15,720 | 2,827 | 4,200 | - | 28 | 26,010 |

**Case 17**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,000 | | | | | | | | | | | | 1,000 |
| **1** | | 3857 | 0.07 | 266 | 157 | 0.17 | 27 | 293 | 0 | 230 | 0 | 1.00 | 496 |
| **2** | | 3857 | 0.07 | 276 | 157 | 0.17 | 27 | 303 | 0 | 230 | 0 | 1.00 | 533 |
| **3** | | 3857 | 0.07 | 287 | 157 | 0.18 | 28 | 314 | 0 | 230 | 0 | 1.00 | 544 |
| **4** | | 3857 | 0.08 | 298 | 157 | 0.18 | 28 | 326 | 0 | 230 | 0 | 1.00 | 556 |
| **5** | | 3857 | 0.08 | 309 | 157 | 0.18 | 29 | 338 | 1120 | 230 | 0 | 1.00 | 1688 |
| **6** | | 3857 | 0.08 | 321 | 157 | 0.19 | 30 | 350 | 0 | 230 | 0 | 1.00 | 580 |
| **7** | | 3857 | 0.09 | 333 | 157 | 0.19 | 30 | 363 | 0 | 230 | 0 | 1.00 | 593 |
| **8** | | 3857 | 0.09 | 346 | 157 | 0.20 | 31 | 376 | 0 | 230 | 0 | 1.00 | 606 |
| **9** | | 3857 | 0.09 | 359 | 157 | 0.20 | 32 | 390 | 0 | 230 | 0 | 1.00 | 620 |
| **10** | | 3857 | 0.10 | 372 | 157 | 0.21 | 32 | 405 | 196 | 230 | 0 | 0.97 | 807 |
| **11** | | 3857 | 0.10 | 386 | 157 | 0.21 | 33 | 419 | 0 | 230 | 0 | 0.97 | 630 |
| **12** | | 3857 | 0.10 | 401 | 157 | 0.21 | 34 | 435 | 0 | 230 | 0 | 0.97 | 643 |
| **13** | | 3857 | 0.11 | 416 | 157 | 0.22 | 34 | 451 | 0 | 230 | 0 | 0.96 | 657 |
| **14** | | 3857 | 0.11 | 432 | 157 | 0.22 | 35 | 467 | 0 | 230 | 0 | 0.96 | 671 |
| **15** | | 3857 | 0.12 | 449 | 157 | 0.23 | 36 | 485 | 196 | 230 | 0 | 0.92 | 838 |
| **16** | | 3857 | 0.12 | 466 | 157 | 0.23 | 37 | 502 | 0 | 230 | 0 | 0.92 | 671 |
| **17** | | 3857 | 0.13 | 483 | 157 | 0.24 | 38 | 521 | 0 | 230 | 0 | 0.91 | 684 |
| **18** | | 3857 | 0.13 | 502 | 157 | 0.24 | 38 | 540 | 0 | 230 | 0 | 0.91 | 698 |
| **19** | | 3857 | 0.14 | 521 | 157 | 0.25 | 39 | 560 | 0 | 230 | 0 | 0.90 | 712 |
| **20** | | 3857 | 0.14 | 541 | 157 | 0.26 | 40 | 581 | 1196 | 230 | 0 | 0.85 | 1697 |
| **21** | | 3857 | 0.15 | 561 | 157 | 0.26 | 41 | 602 | 0 | 230 | 0 | 0.84 | 698 |
| **22** | | 3857 | 0.15 | 582 | 157 | 0.27 | 42 | 624 | 0 | 230 | 0 | 0.83 | 710 |
| **23** | | 3857 | 0.16 | 605 | 157 | 0.27 | 43 | 647 | 0 | 230 | 0 | 0.82 | 723 |
| **24** | | 3857 | 0.16 | 628 | 157 | 0.28 | 44 | 671 | 0 | 230 | 0 | 0.82 | 737 |
| **25** | | 3857 | 0.17 | 651 | 157 | 0.28 | 45 | 696 | 1120 | 230 | 0 | 0.80 | 1636 |
| **26** | | 3857 | 0.18 | 676 | 157 | 0.29 | 46 | 722 | 0 | 230 | 0 | 0.79 | 754 |
| **27** | | 3857 | 0.18 | 702 | 157 | 0.30 | 47 | 749 | 0 | 230 | 0 | 0.79 | 768 |
| **28** | | 3857 | 0.19 | 728 | 157 | 0.30 | 48 | 776 | 0 | 230 | 0 | 0.78 | 783 |
| **29** | | 3857 | 0.20 | 756 | 157 | 0.31 | 49 | 805 | 0 | 230 | 0 | 0.77 | 798 |
| **30** | | 3857 | 0.20 | 785 | 157 | 0.32 | 50 | 835 | 0 | 230 | 245 | 0.76 | 627 |
| **Total** | 1,000 | 115,709 | 4 | 14,437 | 4,712 | 7 | 1,111 | 15,548 | 3,827 | 6,900 | 245 | 28 | 24,159 |

**Case 18**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,000 | | | | | | | | | | | | 1,000 |
| **1** | | 3857 | 0.07 | 266 | 153 | 0.17 | 26 | 292 | 0 | 230 | 0 | 1.00 | 496 |
| **2** | | 3857 | 0.07 | 276 | 153 | 0.17 | 26 | 303 | 0 | 230 | 0 | 1.00 | 533 |
| **3** | | 3857 | 0.07 | 287 | 153 | 0.18 | 27 | 314 | 0 | 230 | 0 | 1.00 | 544 |
| **4** | | 3857 | 0.08 | 298 | 153 | 0.18 | 28 | 325 | 0 | 230 | 0 | 1.00 | 555 |
| **5** | | 3857 | 0.08 | 309 | 153 | 0.18 | 28 | 337 | 1120 | 230 | 0 | 1.00 | 1687 |
| **6** | | 3857 | 0.08 | 321 | 153 | 0.19 | 29 | 349 | 0 | 230 | 0 | 1.00 | 579 |
| **7** | | 3857 | 0.09 | 333 | 153 | 0.19 | 29 | 362 | 0 | 230 | 0 | 1.00 | 592 |
| **8** | | 3857 | 0.09 | 346 | 153 | 0.20 | 30 | 376 | 0 | 230 | 0 | 1.00 | 606 |
| **9** | | 3857 | 0.09 | 359 | 153 | 0.20 | 31 | 389 | 0 | 230 | 0 | 1.00 | 619 |
| **10** | | 3857 | 0.10 | 372 | 153 | 0.21 | 31 | 404 | 196 | 230 | 0 | 0.97 | 806 |
| **11** | | 3857 | 0.10 | 386 | 153 | 0.21 | 32 | 418 | 0 | 230 | 0 | 0.97 | 629 |
| **12** | | 3857 | 0.10 | 401 | 153 | 0.21 | 33 | 434 | 0 | 230 | 0 | 0.97 | 642 |
| **13** | | 3857 | 0.11 | 416 | 153 | 0.22 | 33 | 450 | 0 | 230 | 0 | 0.96 | 656 |
| **14** | | 3857 | 0.11 | 432 | 153 | 0.22 | 34 | 466 | 0 | 230 | 0 | 0.96 | 670 |
| **15** | | 3857 | 0.12 | 449 | 153 | 0.23 | 35 | 484 | 196 | 230 | 0 | 0.92 | 837 |
| **16** | | 3857 | 0.12 | 466 | 153 | 0.23 | 36 | 501 | 0 | 230 | 0 | 0.92 | 670 |
| **17** | | 3857 | 0.13 | 483 | 153 | 0.24 | 37 | 520 | 0 | 230 | 0 | 0.91 | 683 |
| **18** | | 3857 | 0.13 | 502 | 153 | 0.24 | 37 | 539 | 0 | 230 | 0 | 0.91 | 697 |
| **19** | | 3857 | 0.14 | 521 | 153 | 0.25 | 38 | 559 | 0 | 230 | 0 | 0.90 | 711 |
| **20** | | 3857 | 0.14 | 541 | 153 | 0.26 | 39 | 580 | 1196 | 230 | 0 | 0.85 | 1696 |
| **21** | | 3857 | 0.15 | 561 | 153 | 0.26 | 40 | 601 | 0 | 230 | 0 | 0.84 | 697 |
| **22** | | 3857 | 0.15 | 582 | 153 | 0.27 | 41 | 623 | 0 | 230 | 0 | 0.83 | 709 |
| **23** | | 3857 | 0.16 | 605 | 153 | 0.27 | 42 | 646 | 0 | 230 | 0 | 0.82 | 722 |
| **24** | | 3857 | 0.16 | 628 | 153 | 0.28 | 43 | 670 | 0 | 230 | 0 | 0.82 | 736 |
| **25** | | 3857 | 0.17 | 651 | 153 | 0.28 | 43 | 695 | 1120 | 230 | 0 | 0.80 | 1635 |
| **26** | | 3857 | 0.18 | 676 | 153 | 0.29 | 44 | 721 | 0 | 230 | 0 | 0.79 | 753 |
| **27** | | 3857 | 0.18 | 702 | 153 | 0.30 | 45 | 747 | 0 | 230 | 0 | 0.79 | 767 |
| **28** | | 3857 | 0.19 | 728 | 153 | 0.30 | 46 | 775 | 0 | 230 | 0 | 0.78 | 782 |
| **29** | | 3857 | 0.20 | 756 | 153 | 0.31 | 47 | 804 | 0 | 230 | 0 | 0.77 | 797 |
| **30** | | 3857 | 0.20 | 785 | 153 | 0.32 | 48 | 833 | 0 | 230 | 245 | 0.76 | 625 |
| **Total** | 1,000 | 115,709 | 4 | 14,437 | 4,577 | 7 | 1,079 | 15,516 | 3,827 | 6,900 | 245 | 28 | 24,131 |

**Case 20**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 1,250 | | | | | | | | | | | | 1,250 |
| **1** | | 4117 | 0.07 | 284 | 185 | 0.17 | 31 | 315 | 0 | 240 | 0 | 1.00 | 524 |
| **2** | | 4117 | 0.07 | 295 | 185 | 0.17 | 32 | 327 | 0 | 240 | 0 | 1.00 | 567 |
| **3** | | 4117 | 0.07 | 306 | 185 | 0.18 | 33 | 339 | 0 | 240 | 0 | 1.00 | 579 |
| **4** | | 4117 | 0.08 | 318 | 185 | 0.18 | 33 | 351 | 0 | 240 | 0 | 1.00 | 591 |
| **5** | | 4117 | 0.08 | 330 | 185 | 0.18 | 34 | 364 | 1120 | 240 | 0 | 1.00 | 1724 |
| **6** | | 4117 | 0.08 | 342 | 185 | 0.19 | 35 | 377 | 0 | 240 | 0 | 1.00 | 617 |
| **7** | | 4117 | 0.09 | 355 | 185 | 0.19 | 36 | 391 | 0 | 240 | 0 | 1.00 | 631 |
| **8** | | 4117 | 0.09 | 369 | 185 | 0.20 | 36 | 405 | 0 | 240 | 0 | 1.00 | 645 |
| **9** | | 4117 | 0.09 | 383 | 185 | 0.20 | 37 | 420 | 0 | 240 | 0 | 1.00 | 660 |
| **10** | | 4117 | 0.10 | 397 | 185 | 0.21 | 38 | 435 | 196 | 240 | 0 | 0.97 | 847 |
| **11** | | 4117 | 0.10 | 412 | 185 | 0.21 | 39 | 451 | 0 | 240 | 0 | 0.97 | 670 |
| **12** | | 4117 | 0.10 | 428 | 185 | 0.21 | 40 | 468 | 0 | 240 | 0 | 0.97 | 685 |
| **13** | | 4117 | 0.11 | 444 | 185 | 0.22 | 41 | 485 | 0 | 240 | 0 | 0.96 | 699 |
| **14** | | 4117 | 0.11 | 461 | 185 | 0.22 | 42 | 503 | 0 | 240 | 0 | 0.96 | 714 |
| **15** | | 4117 | 0.12 | 479 | 185 | 0.23 | 42 | 521 | | 240 | 0 | 0.92 | 701 |
| **16** | | 4117 | 0.12 | 497 | 185 | 0.23 | 43 | 540 | 0 | 240 | 0 | 0.92 | 715 |
| **17** | | 4117 | 0.13 | 516 | 185 | 0.24 | 44 | 560 | 0 | 240 | 0 | 0.91 | 729 |
| **18** | | 4117 | 0.13 | 536 | 185 | 0.24 | 45 | 581 | 0 | 240 | 0 | 0.91 | 744 |
| **19** | | 4117 | 0.14 | 556 | 185 | 0.25 | 46 | 602 | 0 | 240 | 0 | 0.90 | 759 |
| **20** | | 4117 | 0.14 | 577 | 185 | 0.26 | 47 | 624 | 196 | 240 | 0 | 0.85 | 896 |
| **21** | | 4117 | 0.15 | 599 | 185 | 0.26 | 48 | 647 | 0 | 240 | 0 | 0.84 | 744 |
| **22** | | 4117 | 0.15 | 622 | 185 | 0.27 | 49 | 671 | 0 | 240 | 0 | 0.83 | 758 |
| **23** | | 4117 | 0.16 | 645 | 185 | 0.27 | 51 | 696 | 0 | 240 | 0 | 0.82 | 772 |
| **24** | | 4117 | 0.16 | 670 | 185 | 0.28 | 52 | 722 | 0 | 240 | 0 | 0.82 | 786 |
| **25** | | 4117 | 0.17 | 695 | 185 | 0.28 | 53 | 748 | 1120 | 240 | 0 | 0.80 | 1685 |
| **26** | | 4117 | 0.18 | 722 | 185 | 0.29 | 54 | 776 | 0 | 240 | 0 | 0.79 | 805 |
| **27** | | 4117 | 0.18 | 749 | 185 | 0.30 | 55 | 804 | 0 | 240 | 0 | 0.79 | 820 |
| **28** | | 4117 | 0.19 | 778 | 185 | 0.30 | 56 | 834 | 0 | 240 | 0 | 0.78 | 836 |
| **29** | | 4117 | 0.20 | 807 | 185 | 0.31 | 58 | 865 | 0 | 240 | 0 | 0.77 | 852 |
| **30** | | 4117 | 0.20 | 838 | 185 | 0.32 | 59 | 897 | 0 | 240 | 0 | 0.76 | 869 |
| **Total** | 1,250 | 123,512 | 4 | 15,410 | 5,562 | 7 | 1,311 | 16,722 | 2,632 | 7,200 | - | 28 | 24,874 |

**Case 21**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 2,175 | | | | | | | | | | | | 2,175 |
| **1** | | 3859 | 0.07 | 266 | 174 | 0.17 | 29 | 296 | 0 | 321 | 0 | 1.00 | 587 |
| **2** | | 3859 | 0.07 | 276 | 174 | 0.17 | 30 | 306 | 0 | 321 | 0 | 1.00 | 627 |
| **3** | | 3859 | 0.07 | 287 | 174 | 0.18 | 31 | 318 | 0 | 321 | 0 | 1.00 | 638 |
| **4** | | 3859 | 0.08 | 298 | 174 | 0.18 | 31 | 329 | 0 | 321 | 0 | 1.00 | 650 |
| **5** | | 3859 | 0.08 | 309 | 174 | 0.18 | 32 | 341 | 1120 | 321 | 0 | 1.00 | 1782 |
| **6** | | 3859 | 0.08 | 321 | 174 | 0.19 | 33 | 354 | 0 | 321 | 0 | 1.00 | 674 |
| **7** | | 3859 | 0.09 | 333 | 174 | 0.19 | 33 | 367 | 0 | 321 | 0 | 1.00 | 687 |
| **8** | | 3859 | 0.09 | 346 | 174 | 0.20 | 34 | 380 | 0 | 321 | 0 | 1.00 | 700 |
| **9** | | 3859 | 0.09 | 359 | 174 | 0.20 | 35 | 394 | 0 | 321 | 0 | 1.00 | 714 |
| **10** | | 3859 | 0.10 | 372 | 174 | 0.21 | 36 | 408 | 196 | 321 | 0 | 0.97 | 899 |
| **11** | | 3859 | 0.10 | 387 | 174 | 0.21 | 37 | 423 | 0 | 321 | 0 | 0.97 | 721 |
| **12** | | 3859 | 0.10 | 401 | 174 | 0.21 | 37 | 439 | 0 | 321 | 0 | 0.97 | 734 |
| **13** | | 3859 | 0.11 | 417 | 174 | 0.22 | 38 | 455 | 0 | 321 | 0 | 0.96 | 748 |
| **14** | | 3859 | 0.11 | 432 | 174 | 0.22 | 39 | 471 | 0 | 321 | 0 | 0.96 | 761 |
| **15** | | 3859 | 0.12 | 449 | 174 | 0.23 | 40 | 489 | 196 | 321 | 0 | 0.92 | 925 |
| **16** | | 3859 | 0.12 | 466 | 174 | 0.23 | 41 | 507 | 0 | 321 | 0 | 0.92 | 758 |
| **17** | | 3859 | 0.13 | 484 | 174 | 0.24 | 42 | 525 | 0 | 321 | 0 | 0.91 | 770 |
| **18** | | 3859 | 0.13 | 502 | 174 | 0.24 | 43 | 544 | 0 | 321 | 0 | 0.91 | 784 |
| **19** | | 3859 | 0.14 | 521 | 174 | 0.25 | 43 | 565 | 0 | 321 | 0 | 0.90 | 797 |
| **20** | | 3859 | 0.14 | 541 | 174 | 0.26 | 44 | 585 | 596 | 321 | 0 | 0.85 | 1270 |
| **21** | | 3859 | 0.15 | 561 | 174 | 0.26 | 45 | 607 | 0 | 321 | 0 | 0.84 | 778 |
| **22** | | 3859 | 0.15 | 583 | 174 | 0.27 | 46 | 629 | 0 | 321 | 0 | 0.83 | 790 |
| **23** | | 3859 | 0.16 | 605 | 174 | 0.27 | 47 | 652 | 0 | 321 | 0 | 0.82 | 802 |
| **24** | | 3859 | 0.16 | 628 | 174 | 0.28 | 48 | 676 | 0 | 321 | 0 | 0.82 | 815 |
| **25** | | 3859 | 0.17 | 652 | 174 | 0.28 | 50 | 701 | 1120 | 321 | 0 | 0.80 | 1712 |
| **26** | | 3859 | 0.18 | 676 | 174 | 0.29 | 51 | 727 | 0 | 321 | 0 | 0.79 | 830 |
| **27** | | 3859 | 0.18 | 702 | 174 | 0.30 | 52 | 754 | 0 | 321 | 0 | 0.79 | 844 |
| **28** | | 3859 | 0.19 | 729 | 174 | 0.30 | 53 | 782 | 0 | 321 | 0 | 0.78 | 858 |
| **29** | | 3859 | 0.20 | 757 | 174 | 0.31 | 54 | 811 | 0 | 321 | 0 | 0.77 | 872 |
| **30** | | 3859 | 0.20 | 785 | 174 | 0.32 | 55 | 841 | 0 | 321 | 80 | 0.76 | 826 |
| **Total** | 2,175 | 115,767 | 4 | 14,444 | 5,218 | 7 | 1,230 | 15,674 | 3,227 | 9,615 | 80 | 28 | 27,527 |

**Case 22**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 4,000 | | | | | | | | | | | | 4,000 |
| **1** | | 2139 | 0.07 | 148 | 180 | 0.17 | 30 | 178 | 0 | 290 | 0 | 1.00 | 468 |
| **2** | | 2139 | 0.07 | 153 | 180 | 0.17 | 31 | 184 | 0 | 290 | 0 | 1.00 | 474 |
| **3** | | 2139 | 0.07 | 159 | 180 | 0.18 | 32 | 191 | 0 | 290 | 0 | 1.00 | 481 |
| **4** | | 2139 | 0.08 | 165 | 180 | 0.18 | 33 | 198 | 0 | 290 | 0 | 1.00 | 488 |
| **5** | | 2139 | 0.08 | 171 | 180 | 0.18 | 33 | 205 | 1120 | 290 | 0 | 1.00 | 1615 |
| **6** | | 2139 | 0.08 | 178 | 180 | 0.19 | 34 | 212 | 0 | 290 | 0 | 1.00 | 502 |
| **7** | | 2139 | 0.09 | 185 | 180 | 0.19 | 35 | 219 | 0 | 290 | 0 | 1.00 | 509 |
| **8** | | 2139 | 0.09 | 192 | 180 | 0.20 | 35 | 227 | 0 | 290 | 0 | 1.00 | 517 |
| **9** | | 2139 | 0.09 | 199 | 180 | 0.20 | 36 | 235 | 0 | 290 | 0 | 1.00 | 525 |
| **10** | | 2139 | 0.10 | 206 | 180 | 0.21 | 37 | 243 | 196 | 290 | 0 | 0.97 | 709 |
| **11** | | 2139 | 0.10 | 214 | 180 | 0.21 | 38 | 252 | 0 | 290 | 0 | 0.97 | 526 |
| **12** | | 2139 | 0.10 | 222 | 180 | 0.21 | 39 | 261 | 0 | 290 | 0 | 0.97 | 533 |
| **13** | | 2139 | 0.11 | 231 | 180 | 0.22 | 40 | 270 | 0 | 290 | 0 | 0.96 | 540 |
| **14** | | 2139 | 0.11 | 240 | 180 | 0.22 | 40 | 280 | 0 | 290 | 0 | 0.96 | 548 |
| **15** | | 2139 | 0.12 | 249 | 180 | 0.23 | 41 | 290 | 196 | 290 | 0 | 0.92 | 714 |
| **16** | | 2139 | 0.12 | 258 | 180 | 0.23 | 42 | 300 | 0 | 290 | 0 | 0.92 | 541 |
| **17** | | 2139 | 0.13 | 268 | 180 | 0.24 | 43 | 311 | 0 | 290 | 0 | 0.91 | 548 |
| **18** | | 2139 | 0.13 | 278 | 180 | 0.24 | 44 | 322 | 0 | 290 | 0 | 0.91 | 555 |
| **19** | | 2139 | 0.14 | 289 | 180 | 0.25 | 45 | 334 | 0 | 290 | 0 | 0.90 | 562 |
| **20** | | 2139 | 0.14 | 300 | 180 | 0.26 | 46 | 346 | 3096 | 290 | 0 | 0.85 | 3155 |
| **21** | | 2139 | 0.15 | 311 | 180 | 0.26 | 47 | 358 | 0 | 290 | 0 | 0.84 | 544 |
| **22** | | 2139 | 0.15 | 323 | 180 | 0.27 | 48 | 371 | 0 | 290 | 0 | 0.83 | 550 |
| **23** | | 2139 | 0.16 | 335 | 180 | 0.27 | 49 | 384 | 0 | 290 | 0 | 0.82 | 556 |
| **24** | | 2139 | 0.16 | 348 | 180 | 0.28 | 50 | 398 | 0 | 290 | 0 | 0.82 | 563 |
| **25** | | 2139 | 0.17 | 361 | 180 | 0.28 | 51 | 413 | 1120 | 290 | 0 | 0.80 | 1457 |
| **26** | | 2139 | 0.18 | 375 | 180 | 0.29 | 52 | 427 | 0 | 290 | 0 | 0.79 | 568 |
| **27** | | 2139 | 0.18 | 389 | 180 | 0.30 | 54 | 443 | 0 | 290 | 0 | 0.79 | 575 |
| **28** | | 2139 | 0.19 | 404 | 180 | 0.30 | 55 | 459 | 0 | 290 | 0 | 0.78 | 583 |
| **29** | | 2139 | 0.20 | 419 | 180 | 0.31 | 56 | 475 | 0 | 290 | 0 | 0.77 | 590 |
| **30** | | 2139 | 0.20 | 435 | 180 | 0.32 | 57 | 492 | 0 | 290 | 1225 | 0.76 | -338 |
| **Total** | 4,000 | 64,158 | 4 | 8,005 | 5,408 | 7 | 1,275 | 9,280 | 5,727 | 8,700 | 1,225 | 28 | 24,156 |

| Case 23 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 7,444 | | | | | | | | | | | | 7,444 |
| **1** | | 1490 | 0.07 | 103 | 113 | 0.17 | 19 | 122 | 0 | 290 | 0 | 1.00 | 412 |
| **2** | | 1490 | 0.07 | 107 | 113 | 0.17 | 20 | 126 | 0 | 290 | 0 | 1.00 | 416 |
| **3** | | 1490 | 0.07 | 111 | 113 | 0.18 | 20 | 131 | 0 | 290 | 0 | 1.00 | 421 |
| **4** | | 1490 | 0.08 | 115 | 113 | 0.18 | 20 | 135 | 0 | 290 | 0 | 1.00 | 425 |
| **5** | | 1490 | 0.08 | 119 | 113 | 0.18 | 21 | 140 | 196 | 290 | 0 | 1.00 | 626 |
| **6** | | 1490 | 0.08 | 124 | 113 | 0.19 | 21 | 145 | 0 | 290 | 0 | 1.00 | 435 |
| **7** | | 1490 | 0.09 | 129 | 113 | 0.19 | 22 | 150 | 0 | 290 | 0 | 1.00 | 440 |
| **8** | | 1490 | 0.09 | 134 | 113 | 0.20 | 22 | 156 | 0 | 290 | 0 | 1.00 | 446 |
| **9** | | 1490 | 0.09 | 139 | 113 | 0.20 | 23 | 161 | 0 | 290 | 0 | 1.00 | 451 |
| **10** | | 1490 | 0.10 | 144 | 113 | 0.21 | 23 | 167 | 196 | 290 | 0 | 0.97 | 635 |
| **11** | | 1490 | 0.10 | 149 | 113 | 0.21 | 24 | 173 | 0 | 290 | 0 | 0.97 | 449 |
| **12** | | 1490 | 0.10 | 155 | 113 | 0.21 | 24 | 179 | 0 | 290 | 0 | 0.97 | 454 |
| **13** | | 1490 | 0.11 | 161 | 113 | 0.22 | 25 | 186 | 0 | 290 | 0 | 0.96 | 459 |
| **14** | | 1490 | 0.11 | 167 | 113 | 0.22 | 25 | 192 | 0 | 290 | 0 | 0.96 | 464 |
| **15** | | 1490 | 0.12 | 173 | 113 | 0.23 | 26 | 199 | 196 | 290 | 0 | 0.92 | 631 |
| **16** | | 1490 | 0.12 | 180 | 113 | 0.23 | 26 | 206 | 0 | 290 | 0 | 0.92 | 455 |
| **17** | | 1490 | 0.13 | 187 | 113 | 0.24 | 27 | 214 | 0 | 290 | 0 | 0.91 | 459 |
| **18** | | 1490 | 0.13 | 194 | 113 | 0.24 | 28 | 222 | 0 | 290 | 0 | 0.91 | 463 |
| **19** | | 1490 | 0.14 | 201 | 113 | 0.25 | 28 | 229 | 0 | 290 | 0 | 0.90 | 468 |
| **20** | | 1490 | 0.14 | 209 | 113 | 0.26 | 29 | 238 | 3096 | 290 | 0 | 0.85 | 3064 |
| **21** | | 1490 | 0.15 | 217 | 113 | 0.26 | 30 | 246 | 0 | 290 | 0 | 0.84 | 450 |
| **22** | | 1490 | 0.15 | 225 | 113 | 0.27 | 30 | 255 | 0 | 290 | 0 | 0.83 | 453 |
| **23** | | 1490 | 0.16 | 234 | 113 | 0.27 | 31 | 264 | 0 | 290 | 0 | 0.82 | 457 |
| **24** | | 1490 | 0.16 | 242 | 113 | 0.28 | 32 | 274 | 0 | 290 | 0 | 0.82 | 461 |
| **25** | | 1490 | 0.17 | 252 | 113 | 0 | 32 | 284 | 196 | 290 | 0 | 0.80 | 615 |
| **26** | | 1490 | 0.18 | 261 | 113 | 0 | 33 | 294 | 0 | 290 | 0 | 0.79 | 463 |
| **27** | | 1490 | 0.18 | 271 | 113 | 0 | 34 | 305 | 0 | 290 | 0 | 0.79 | 467 |
| **28** | | 1490 | 0.19 | 282 | 113 | 0 | 34 | 316 | 0 | 290 | 0 | 0.78 | 471 |
| **29** | | 1490 | 0.20 | 292 | 113 | 0 | 35 | 327 | 0 | 290 | 0 | 0.77 | 476 |
| **30** | | 1490 | 0.20 | 303 | 113 | 0 | 36 | 339 | 0 | 290 | 1375 | 0.76 | -570 |
| **Total** | 7,444 | 44,713 | 4 | 5,579 | 3,392 | 7 | 799 | 6,378 | 3,878 | 8,700 | 1,375 | 28 | 23,261 |

| Case 24 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 7,864 | | | | | | | | | | | | 7,864 |
| **1** | | 1463 | 0.07 | 101 | 110 | 0.17 | 19 | 120 | 0 | 330 | 0 | 1.00 | 450 |
| **2** | | 1463 | 0.07 | 105 | 110 | 0.17 | 19 | 124 | 0 | 330 | 0 | 1.00 | 454 |
| **3** | | 1463 | 0.07 | 109 | 110 | 0.18 | 19 | 128 | 0 | 330 | 0 | 1.00 | 458 |
| **4** | | 1463 | 0.08 | 113 | 110 | 0.18 | 20 | 133 | 0 | 330 | 0 | 1.00 | 463 |
| **5** | | 1463 | 0.08 | 117 | 110 | 0.18 | 20 | 137 | 196 | 330 | 0 | 1.00 | 663 |
| **6** | | 1463 | 0.08 | 122 | 110 | 0.19 | 21 | 142 | 0 | 330 | 0 | 1.00 | 472 |
| **7** | | 1463 | 0.09 | 126 | 110 | 0.19 | 21 | 147 | 0 | 330 | 0 | 1.00 | 477 |
| **8** | | 1463 | 0.09 | 131 | 110 | 0.20 | 22 | 153 | 0 | 330 | 0 | 1.00 | 483 |
| **9** | | 1463 | 0.09 | 136 | 110 | 0.20 | 22 | 158 | 0 | 330 | 0 | 1.00 | 488 |
| **10** | | 1463 | 0.10 | 141 | 110 | 0.21 | 23 | 164 | 196 | 330 | 0 | 0.97 | 670 |
| **11** | | 1463 | 0.10 | 147 | 110 | 0.21 | 23 | 170 | 0 | 330 | 0 | 0.97 | 485 |
| **12** | | 1463 | 0.10 | 152 | 110 | 0.21 | 24 | 176 | 0 | 330 | 0 | 0.97 | 489 |
| **13** | | 1463 | 0.11 | 158 | 110 | 0.22 | 24 | 182 | 0 | 330 | 0 | 0.96 | 494 |
| **14** | | 1463 | 0.11 | 164 | 110 | 0.22 | 25 | 189 | 0 | 330 | 0 | 0.96 | 499 |
| **15** | | 1463 | 0.12 | 170 | 110 | 0.23 | 25 | 195 | 196 | 330 | 0 | 0.92 | 664 |
| **16** | | 1463 | 0.12 | 177 | 110 | 0.23 | 26 | 202 | 0 | 330 | 0 | 0.92 | 488 |
| **17** | | 1463 | 0.13 | 183 | 110 | 0.24 | 26 | 210 | 0 | 330 | 0 | 0.91 | 492 |
| **18** | | 1463 | 0.13 | 190 | 110 | 0.24 | 27 | 217 | 0 | 330 | 0 | 0.91 | 496 |
| **19** | | 1463 | 0.14 | 198 | 110 | 0.25 | 28 | 225 | 0 | 330 | 0 | 0.90 | 500 |
| **20** | | 1463 | 0.14 | 205 | 110 | 0.26 | 28 | 233 | 3096 | 330 | 0 | 0.85 | 3094 |
| **21** | | 1463 | 0.15 | 213 | 110 | 0.26 | 29 | 242 | 0 | 330 | 0 | 0.84 | 479 |
| **22** | | 1463 | 0.15 | 221 | 110 | 0.27 | 29 | 250 | 0 | 330 | 0 | 0.83 | 483 |
| **23** | | 1463 | 0.16 | 229 | 110 | 0.27 | 30 | 259 | 0 | 330 | 0 | 0.82 | 486 |
| **24** | | 1463 | 0.16 | 238 | 110 | 0.28 | 31 | 269 | 0 | 330 | 0 | 0.82 | 490 |
| **25** | | 1463 | 0.17 | 247 | 110 | 0.28 | 31 | 278 | 196 | 330 | 0 | 0.80 | 643 |
| **26** | | 1463 | 0.18 | 256 | 110 | 0.29 | 32 | 289 | 0 | 330 | 0 | 0.79 | 490 |
| **27** | | 1463 | 0.18 | 266 | 110 | 0.30 | 33 | 299 | 0 | 330 | 0 | 0.79 | 494 |
| **28** | | 1463 | 0.19 | 276 | 110 | 0.30 | 34 | 310 | 0 | 330 | 0 | 0.78 | 498 |
| **29** | | 1463 | 0.20 | 287 | 110 | 0.31 | 34 | 321 | 0 | 330 | 0 | 0.77 | 502 |
| **30** | | 1463 | 0.20 | 298 | 110 | 0.32 | 35 | 333 | 0 | 330 | 1375 | 0.76 | -544 |
| **Total** | 7,864 | 43,888 | 4 | 5,476 | 3,307 | 7 | 779 | 6,255 | 3,878 | 9,900 | 1,375 | 28 | 24,662 |

**Case 25**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 8,444 | | | | | | | | | | | | 8,444 |
| **1** | | 1478 | 0.07 | 102 | 102 | 0.17 | 17 | 119 | 0 | 330 | 0 | 1.00 | 449 |
| **2** | | 1478 | 0.07 | 106 | 102 | 0.17 | 18 | 123 | 0 | 330 | 0 | 1.00 | 453 |
| **3** | | 1478 | 0.07 | 110 | 102 | 0.18 | 18 | 128 | 0 | 330 | 0 | 1.00 | 458 |
| **4** | | 1478 | 0.08 | 114 | 102 | 0.18 | 18 | 132 | 0 | 330 | 0 | 1.00 | 462 |
| **5** | | 1478 | 0.08 | 118 | 102 | 0.18 | 19 | 137 | 196 | 330 | 0 | 1.00 | 663 |
| **6** | | 1478 | 0.08 | 123 | 102 | 0.19 | 19 | 142 | 0 | 330 | 0 | 1.00 | 472 |
| **7** | | 1478 | 0.09 | 128 | 102 | 0.19 | 20 | 147 | 0 | 330 | 0 | 1.00 | 477 |
| **8** | | 1478 | 0.09 | 132 | 102 | 0.20 | 20 | 152 | 0 | 330 | 0 | 1.00 | 482 |
| **9** | | 1478 | 0.09 | 137 | 102 | 0.20 | 20 | 158 | 0 | 330 | 0 | 1.00 | 488 |
| **10** | | 1478 | 0.10 | 143 | 102 | 0.21 | 21 | 164 | 196 | 330 | 0 | 0.97 | 670 |
| **11** | | 1478 | 0.10 | 148 | 102 | 0.21 | 21 | 169 | 0 | 330 | 0 | 0.97 | 484 |
| **12** | | 1478 | 0.10 | 154 | 102 | 0.21 | 22 | 176 | 0 | 330 | 0 | 0.97 | 489 |
| **13** | | 1478 | 0.11 | 160 | 102 | 0.22 | 22 | 182 | 0 | 330 | 0 | 0.96 | 494 |
| **14** | | 1478 | 0.11 | 166 | 102 | 0.22 | 23 | 188 | 0 | 330 | 0 | 0.96 | 498 |
| **15** | | 1478 | 0.12 | 172 | 102 | 0.23 | 23 | 195 | 196 | 330 | 0 | 0.92 | 664 |
| **16** | | 1478 | 0.12 | 178 | 102 | 0.23 | 24 | 202 | 0 | 330 | 0 | 0.92 | 488 |
| **17** | | 1478 | 0.13 | 185 | 102 | 0.24 | 24 | 210 | 0 | 330 | 0 | 0.91 | 491 |
| **18** | | 1478 | 0.13 | 192 | 102 | 0.24 | 25 | 217 | 0 | 330 | 0 | 0.91 | 496 |
| **19** | | 1478 | 0.14 | 200 | 102 | 0.25 | 25 | 225 | 0 | 330 | 0 | 0.90 | 500 |
| **20** | | 1478 | 0.14 | 207 | 102 | 0.26 | 26 | 233 | 4096 | 330 | 0 | 0.85 | 3939 |
| **21** | | 1478 | 0.15 | 215 | 102 | 0.26 | 27 | 242 | 0 | 330 | 0 | 0.84 | 479 |
| **22** | | 1478 | 0.15 | 223 | 102 | 0.27 | 27 | 250 | 0 | 330 | 0 | 0.83 | 483 |
| **23** | | 1478 | 0.16 | 232 | 102 | 0.27 | 28 | 259 | 0 | 330 | 0 | 0.82 | 486 |
| **24** | | 1478 | 0.16 | 240 | 102 | 0.28 | 28 | 269 | 0 | 330 | 0 | 0.82 | 490 |
| **25** | | 1478 | 0.17 | 250 | 102 | 0.28 | 29 | 279 | 196 | 330 | 0 | 0.80 | 643 |
| **26** | | 1478 | 0.18 | 259 | 102 | 0.29 | 30 | 289 | 0 | 330 | 0 | 0.79 | 490 |
| **27** | | 1478 | 0.18 | 269 | 102 | 0.30 | 30 | 299 | 0 | 330 | 0 | 0.79 | 494 |
| **28** | | 1478 | 0.19 | 279 | 102 | 0.30 | 31 | 310 | 0 | 330 | 0 | 0.78 | 498 |
| **29** | | 1478 | 0.20 | 290 | 102 | 0.31 | 32 | 321 | 0 | 330 | 0 | 0.77 | 502 |
| **30** | | 1478 | 0.20 | 301 | 102 | 0.32 | 32 | 333 | 0 | 330 | 1620 | 0.76 | -731 |
| **Total** | 8,444 | 44,328 | 4 | 5,531 | 3,053 | 7 | 720 | 6,250 | 4,878 | 9,900 | 1,620 | 28 | 25,895 |

**Case 26**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 8,864 | | | | | | | | | | | | 8,864 |
| **1** | | 1450 | 0.07 | 100 | 93 | 0.17 | 16 | 116 | 0 | 330 | 0 | 1.00 | 446 |
| **2** | | 1450 | 0.07 | 104 | 93 | 0.17 | 16 | 120 | 0 | 330 | 0 | 1.00 | 450 |
| **3** | | 1450 | 0.07 | 108 | 93 | 0.18 | 16 | 124 | 0 | 330 | 0 | 1.00 | 454 |
| **4** | | 1450 | 0.08 | 112 | 93 | 0.18 | 17 | 129 | 0 | 330 | 0 | 1.00 | 459 |
| **5** | | 1450 | 0.08 | 116 | 93 | 0.18 | 17 | 133 | 196 | 330 | 0 | 1.00 | 659 |
| **6** | | 1450 | 0.08 | 121 | 93 | 0.19 | 18 | 138 | 0 | 330 | 0 | 1.00 | 468 |
| **7** | | 1450 | 0.09 | 125 | 93 | 0.19 | 18 | 143 | 0 | 330 | 0 | 1.00 | 473 |
| **8** | | 1450 | 0.09 | 130 | 93 | 0.20 | 18 | 148 | 0 | 330 | 0 | 1.00 | 478 |
| **9** | | 1450 | 0.09 | 135 | 93 | 0.20 | 19 | 154 | 0 | 330 | 0 | 1.00 | 484 |
| **10** | | 1450 | 0.10 | 140 | 93 | 0.21 | 19 | 159 | 196 | 330 | 0 | 0.97 | 666 |
| **11** | | 1450 | 0.10 | 145 | 93 | 0.21 | 20 | 165 | 0 | 330 | 0 | 0.97 | 480 |
| **12** | | 1450 | 0.10 | 151 | 93 | 0.21 | 20 | 171 | 0 | 330 | 0 | 0.97 | 484 |
| **13** | | 1450 | 0.11 | 157 | 93 | 0.22 | 20 | 177 | 0 | 330 | 0 | 0.96 | 489 |
| **14** | | 1450 | 0.11 | 162 | 93 | 0.22 | 21 | 183 | 0 | 330 | 0 | 0.96 | 494 |
| **15** | | 1450 | 0.12 | 169 | 93 | 0.23 | 21 | 190 | 196 | 330 | 0 | 0.92 | 659 |
| **16** | | 1450 | 0.12 | 175 | 93 | 0.23 | 22 | 197 | 0 | 330 | 0 | 0.92 | 483 |
| **17** | | 1450 | 0.13 | 182 | 93 | 0.24 | 22 | 204 | 0 | 330 | 0 | 0.91 | 486 |
| **18** | | 1450 | 0.13 | 189 | 93 | 0.24 | 23 | 211 | 0 | 330 | 0 | 0.91 | 490 |
| **19** | | 1450 | 0.14 | 196 | 93 | 0.25 | 23 | 219 | 0 | 330 | 0 | 0.90 | 495 |
| **20** | | 1450 | 0.14 | 203 | 93 | 0.26 | 24 | 227 | 4096 | 330 | 0 | 0.85 | 3934 |
| **21** | | 1450 | 0.15 | 211 | 93 | 0.26 | 24 | 235 | 0 | 330 | 0 | 0.84 | 474 |
| **22** | | 1450 | 0.15 | 219 | 93 | 0.27 | 25 | 244 | 0 | 330 | 0 | 0.83 | 477 |
| **23** | | 1450 | 0.16 | 227 | 93 | 0.27 | 25 | 253 | 0 | 330 | 0 | 0.82 | 480 |
| **24** | | 1450 | 0.16 | 236 | 93 | 0.28 | 26 | 262 | 0 | 330 | 0 | 0.82 | 484 |
| **25** | | 1450 | 0.17 | 245 | 93 | 0.28 | 27 | 271 | 196 | 330 | 0 | 0.80 | 637 |
| **26** | | 1450 | 0.18 | 254 | 93 | 0.29 | 27 | 281 | 0 | 330 | 0 | 0.79 | 484 |
| **27** | | 1450 | 0.18 | 264 | 93 | 0.30 | 28 | 292 | 0 | 330 | 0 | 0.79 | 488 |
| **28** | | 1450 | 0.19 | 274 | 93 | 0.30 | 28 | 302 | 0 | 330 | 0 | 0.78 | 492 |
| **29** | | 1450 | 0.20 | 284 | 93 | 0.31 | 29 | 313 | 0 | 330 | 0 | 0.77 | 496 |
| **30** | | 1450 | 0.20 | 295 | 93 | 0.32 | 30 | 325 | 0 | 330 | 1620 | 0.76 | -738 |
| **Total** | 8,864 | 43,500 | 4 | 5,427 | 2,795 | 7 | 659 | 6,086 | 4,878 | 9,900 | 1,620 | 28 | 26,170 |

| Case 27 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 8,864 | | | | | | | | | | | | 8,864 |
| **1** | | 1450 | 0.07 | 100 | 93 | 0.17 | 16 | 116 | 0 | 330 | 0 | 1.00 | 427 |
| **2** | | 1450 | 0.07 | 104 | 93 | 0.17 | 16 | 120 | 0 | 330 | 0 | 1.00 | 430 |
| **3** | | 1450 | 0.07 | 108 | 93 | 0.18 | 16 | 124 | 0 | 330 | 0 | 1.00 | 434 |
| **4** | | 1450 | 0.08 | 112 | 93 | 0.18 | 17 | 129 | 0 | 330 | 0 | 1.00 | 437 |
| **5** | | 1450 | 0.08 | 116 | 93 | 0.18 | 17 | 133 | 196 | 330 | 0 | 1.00 | 441 |
| **6** | | 1450 | 0.08 | 121 | 93 | 0.19 | 18 | 138 | 0 | 330 | 0 | 1.00 | 445 |
| **7** | | 1450 | 0.09 | 125 | 93 | 0.19 | 18 | 143 | 0 | 330 | 0 | 1.00 | 449 |
| **8** | | 1450 | 0.09 | 130 | 93 | 0.20 | 18 | 148 | 0 | 330 | 0 | 1.00 | 453 |
| **9** | | 1450 | 0.09 | 135 | 93 | 0.20 | 19 | 154 | 0 | 330 | 0 | 1.00 | 458 |
| **10** | | 1450 | 0.10 | 140 | 93 | 0.21 | 19 | 159 | 196 | 330 | 0 | 0.97 | 449 |
| **11** | | 1450 | 0.10 | 145 | 93 | 0.21 | 20 | 165 | 0 | 330 | 0 | 0.97 | 453 |
| **12** | | 1450 | 0.10 | 151 | 93 | 0.21 | 20 | 171 | 0 | 330 | 0 | 0.97 | 456 |
| **13** | | 1450 | 0.11 | 157 | 93 | 0.22 | 20 | 177 | 0 | 330 | 0 | 0.96 | 460 |
| **14** | | 1450 | 0.11 | 162 | 93 | 0.22 | 21 | 183 | 0 | 330 | 0 | 0.96 | 463 |
| **15** | | 1450 | 0.12 | 169 | 93 | 0.23 | 21 | 190 | 196 | 330 | 0 | 0.92 | 629 |
| **16** | | 1450 | 0.12 | 175 | 93 | 0.23 | 22 | 197 | 0 | 330 | 0 | 0.92 | 451 |
| **17** | | 1450 | 0.13 | 182 | 93 | 0.24 | 22 | 204 | 0 | 330 | 0 | 0.91 | 454 |
| **18** | | 1450 | 0.13 | 189 | 93 | 0.24 | 23 | 211 | 0 | 330 | 0 | 0.91 | 457 |
| **19** | | 1450 | 0.14 | 196 | 93 | 0.25 | 23 | 219 | 0 | 330 | 0 | 0.90 | 460 |
| **20** | | 1450 | 0.14 | 203 | 93 | 0.26 | 24 | 227 | 4096 | 330 | 0 | 0.85 | 2889 |
| **21** | | 1450 | 0.15 | 211 | 93 | 0.26 | 24 | 235 | 0 | 330 | 0 | 0.84 | 439 |
| **22** | | 1450 | 0.15 | 219 | 93 | 0.27 | 25 | 244 | 0 | 330 | 0 | 0.83 | 441 |
| **23** | | 1450 | 0.16 | 227 | 93 | 0.27 | 25 | 253 | 0 | 330 | 0 | 0.82 | 443 |
| **24** | | 1450 | 0.16 | 236 | 93 | 0.28 | 26 | 262 | 0 | 330 | 0 | 0.82 | 446 |
| **25** | | 1450 | 0.17 | 245 | 93 | 0.28 | 27 | 271 | 196 | 330 | 0 | 0.80 | 442 |
| **26** | | 1450 | 0.18 | 254 | 93 | 0.29 | 27 | 281 | 0 | 330 | 0 | 0.79 | 444 |
| **27** | | 1450 | 0.18 | 264 | 93 | 0.30 | 28 | 292 | 0 | 330 | 0 | 0.79 | 447 |
| **28** | | 1450 | 0.19 | 274 | 93 | 0.30 | 28 | 302 | 0 | 330 | 0 | 0.78 | 449 |
| **29** | | 1450 | 0.20 | 284 | 93 | 0.31 | 29 | 313 | 0 | 330 | 0 | 0.77 | 452 |
| **30** | | 1450 | 0.20 | 295 | 93 | 0.32 | 30 | 325 | 0 | 330 | 1620 | 0.76 | -596 |
| **Total** | 8,864 | 43,500 | 4 | 5,427 | 2,795 | 7 | 659 | 6,086 | 4,878 | 9,900 | 1,620 | 28 | 23,968 |

| Case 28 | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 9,385 | | | | | | | | | | | | 9,385 |
| **1** | | 1099 | 0.07 | 76 | 108 | 0.17 | 18 | 94 | 0 | 330 | 0 | 1.00 | 424 |
| **2** | | 1099 | 0.07 | 79 | 108 | 0.17 | 19 | 97 | 0 | 330 | 0 | 1.00 | 427 |
| **3** | | 1099 | 0.07 | 82 | 108 | 0.18 | 19 | 101 | 0 | 330 | 0 | 1.00 | 431 |
| **4** | | 1099 | 0.08 | 85 | 108 | 0.18 | 19 | 104 | 0 | 330 | 0 | 1.00 | 434 |
| **5** | | 1099 | 0.08 | 88 | 108 | 0.18 | 20 | 108 | 0 | 330 | 0 | 1.00 | 438 |
| **6** | | 1099 | 0.08 | 91 | 108 | 0.19 | 20 | 112 | 0 | 330 | 0 | 1.00 | 442 |
| **7** | | 1099 | 0.09 | 95 | 108 | 0.19 | 21 | 116 | 0 | 330 | 0 | 1.00 | 446 |
| **8** | | 1099 | 0.09 | 98 | 108 | 0.20 | 21 | 120 | 0 | 330 | 0 | 1.00 | 450 |
| **9** | | 1099 | 0.09 | 102 | 108 | 0.20 | 22 | 124 | 0 | 330 | 0 | 1.00 | 454 |
| **10** | | 1099 | 0.10 | 106 | 108 | 0.21 | 22 | 128 | 0 | 330 | 0 | 0.97 | 446 |
| **11** | | 1099 | 0.10 | 110 | 108 | 0.21 | 23 | 133 | 0 | 330 | 0 | 0.97 | 449 |
| **12** | | 1099 | 0.10 | 114 | 108 | 0.21 | 23 | 137 | 0 | 330 | 0 | 0.97 | 452 |
| **13** | | 1099 | 0.11 | 119 | 108 | 0.22 | 24 | 142 | 0 | 330 | 0 | 0.96 | 455 |
| **14** | | 1099 | 0.11 | 123 | 108 | 0.22 | 24 | 147 | 0 | 330 | 0 | 0.96 | 459 |
| **15** | | 1099 | 0.12 | 128 | 108 | 0.23 | 25 | 153 | 196 | 330 | 0 | 0.92 | 625 |
| **16** | | 1099 | 0.12 | 133 | 108 | 0.23 | 25 | 158 | 0 | 330 | 0 | 0.92 | 447 |
| **17** | | 1099 | 0.13 | 138 | 108 | 0.24 | 26 | 164 | 0 | 330 | 0 | 0.91 | 450 |
| **18** | | 1099 | 0.13 | 143 | 108 | 0.24 | 26 | 169 | 0 | 330 | 0 | 0.91 | 452 |
| **19** | | 1099 | 0.14 | 148 | 108 | 0.25 | 27 | 175 | 0 | 330 | 0 | 0.90 | 455 |
| **20** | | 1099 | 0.14 | 154 | 108 | 0.26 | 27 | 182 | 2900 | 330 | 0 | 0.85 | 2885 |
| **21** | | 1099 | 0.15 | 160 | 108 | 0.26 | 28 | 188 | 0 | 330 | 0 | 0.84 | 434 |
| **22** | | 1099 | 0.15 | 166 | 108 | 0.27 | 29 | 195 | 0 | 330 | 0 | 0.83 | 436 |
| **23** | | 1099 | 0.16 | 172 | 108 | 0.27 | 29 | 202 | 0 | 330 | 0 | 0.82 | 438 |
| **24** | | 1099 | 0.16 | 179 | 108 | 0.28 | 30 | 209 | 0 | 330 | 0 | 0.82 | 441 |
| **25** | | 1099 | 0.17 | 186 | 108 | 0.28 | 31 | 216 | 0 | 330 | 0 | 0.80 | 437 |
| **26** | | 1099 | 0.18 | 193 | 108 | 0.29 | 31 | 224 | 0 | 330 | 0 | 0.79 | 439 |
| **27** | | 1099 | 0.18 | 200 | 108 | 0.30 | 32 | 232 | 0 | 330 | 0 | 0.79 | 441 |
| **28** | | 1099 | 0.19 | 208 | 108 | 0.30 | 33 | 240 | 0 | 330 | 0 | 0.78 | 444 |
| **29** | | 1099 | 0.20 | 216 | 108 | 0.31 | 33 | 249 | 0 | 330 | 0 | 0.77 | 446 |
| **30** | | 1099 | 0.20 | 224 | 108 | 0.32 | 34 | 258 | | 330 | 1375 | 0.76 | -602 |
| **Total** | 9,385 | 32,984 | 4 | 4,115 | 3,227 | 7 | 761 | 4,876 | 3,096 | 9,900 | 1,375 | 28 | 24,260 |

| Case 29 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 9,063 | | | | | | | | | | | | 9,063 |
| **1** | | 1115 | 0.07 | 77 | 111 | 0.17 | 19 | 96 | 0 | 290 | 0 | 1.00 | 386 |
| **2** | | 1115 | 0.07 | 80 | 111 | 0.17 | 19 | 99 | 0 | 290 | 0 | 1.00 | 389 |
| **3** | | 1115 | 0.07 | 83 | 111 | 0.18 | 20 | 102 | 0 | 290 | 0 | 1.00 | 392 |
| **4** | | 1115 | 0.08 | 86 | 111 | 0.18 | 20 | 106 | 0 | 290 | 0 | 1.00 | 396 |
| **5** | | 1115 | 0.08 | 89 | 111 | 0.18 | 20 | 110 | 0 | 290 | 0 | 1.00 | 400 |
| **6** | | 1115 | 0.08 | 93 | 111 | 0.19 | 21 | 113 | 0 | 290 | 0 | 1.00 | 403 |
| **7** | | 1115 | 0.09 | 96 | 111 | 0.19 | 21 | 117 | 0 | 290 | 0 | 1.00 | 407 |
| **8** | | 1115 | 0.09 | 100 | 111 | 0.20 | 22 | 122 | 0 | 290 | 0 | 1.00 | 412 |
| **9** | | 1115 | 0.09 | 104 | 111 | 0.20 | 22 | 126 | 0 | 290 | 0 | 1.00 | 416 |
| **10** | | 1115 | 0.10 | 108 | 111 | 0.21 | 23 | 130 | 0 | 290 | 0 | 0.97 | 409 |
| **11** | | 1115 | 0.10 | 112 | 111 | 0.21 | 23 | 135 | 0 | 290 | 0 | 0.97 | 412 |
| **12** | | 1115 | 0.10 | 116 | 111 | 0.21 | 24 | 140 | 0 | 290 | 0 | 0.97 | 415 |
| **13** | | 1115 | 0.11 | 120 | 111 | 0.22 | 24 | 145 | 0 | 290 | 0 | 0.96 | 419 |
| **14** | | 1115 | 0.11 | 125 | 111 | 0.22 | 25 | 150 | 0 | 290 | 0 | 0.96 | 423 |
| **15** | | 1115 | 0.12 | 130 | 111 | 0.23 | 25 | 155 | 196 | 290 | 0 | 0.92 | 590 |
| **16** | | 1115 | 0.12 | 135 | 111 | 0.23 | 26 | 160 | 0 | 290 | 0 | 0.92 | 413 |
| **17** | | 1115 | 0.13 | 140 | 111 | 0.24 | 26 | 166 | 0 | 290 | 0 | 0.91 | 416 |
| **18** | | 1115 | 0.13 | 145 | 111 | 0.24 | 27 | 172 | 0 | 290 | 0 | 0.91 | 419 |
| **19** | | 1115 | 0.14 | 150 | 111 | 0.25 | 28 | 178 | 0 | 290 | 0 | 0.90 | 422 |
| **20** | | 1115 | 0.14 | 156 | 111 | 0.26 | 28 | 184 | 2900 | 290 | 0 | 0.85 | 2853 |
| **21** | | 1115 | 0.15 | 162 | 111 | 0.26 | 29 | 191 | 0 | 290 | 0 | 0.84 | 403 |
| **22** | | 1115 | 0.15 | 168 | 111 | 0.27 | 29 | 198 | 0 | 290 | 0 | 0.83 | 406 |
| **23** | | 1115 | 0.16 | 175 | 111 | 0.27 | 30 | 205 | 0 | 290 | 0 | 0.82 | 408 |
| **24** | | 1115 | 0.16 | 181 | 111 | 0.28 | 31 | 212 | 0 | 290 | 0 | 0.82 | 411 |
| **25** | | 1115 | 0.17 | 188 | 111 | 0.28 | 31 | 220 | 0 | 290 | 0 | 0.80 | 407 |
| **26** | | 1115 | 0.18 | 195 | 111 | 0.29 | 32 | 228 | 0 | 290 | 0 | 0.79 | 410 |
| **27** | | 1115 | 0.18 | 203 | 111 | 0.30 | 33 | 236 | 0 | 290 | 0 | 0.79 | 413 |
| **28** | | 1115 | 0.19 | 211 | 111 | 0.30 | 34 | 244 | 0 | 290 | 0 | 0.78 | 416 |
| **29** | | 1115 | 0.20 | 219 | 111 | 0.31 | 34 | 253 | 0 | 290 | 0 | 0.77 | 419 |
| **30** | | 1115 | 0.20 | 227 | 111 | 0.32 | 35 | 262 | | 290 | 1375 | 0.76 | -629 |
| **Total** | 9,063 | 33,437 | 4 | 4,172 | 3,317 | 7 | 782 | 4,954 | 3,096 | 8,700 | 1,375 | 28 | 22,917 |

| Case 30 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 9,483 | | | | | | | | | | | | 9,483 |
| **1** | | 1082 | 0.07 | 75 | 107 | 0.17 | 18 | 93 | 0 | 290 | 0 | 1.00 | 383 |
| **2** | | 1082 | 0.07 | 77 | 107 | 0.17 | 19 | 96 | 0 | 290 | 0 | 1.00 | 386 |
| **3** | | 1082 | 0.07 | 80 | 107 | 0.18 | 19 | 99 | 0 | 290 | 0 | 1.00 | 389 |
| **4** | | 1082 | 0.08 | 83 | 107 | 0.18 | 19 | 103 | 0 | 290 | 0 | 1.00 | 393 |
| **5** | | 1082 | 0.08 | 87 | 107 | 0.18 | 20 | 106 | 0 | 290 | 0 | 1.00 | 396 |
| **6** | | 1082 | 0.08 | 90 | 107 | 0.19 | 20 | 110 | 0 | 290 | 0 | 1.00 | 400 |
| **7** | | 1082 | 0.09 | 93 | 107 | 0.19 | 21 | 114 | 0 | 290 | 0 | 1.00 | 404 |
| **8** | | 1082 | 0.09 | 97 | 107 | 0.20 | 21 | 118 | 0 | 290 | 0 | 1.00 | 408 |
| **9** | | 1082 | 0.09 | 101 | 107 | 0.20 | 22 | 122 | 0 | 290 | 0 | 1.00 | 412 |
| **10** | | 1082 | 0.10 | 104 | 107 | 0.21 | 22 | 126 | 0 | 290 | 0 | 0.97 | 405 |
| **11** | | 1082 | 0.10 | 108 | 107 | 0.21 | 23 | 131 | 0 | 290 | 0 | 0.97 | 408 |
| **12** | | 1082 | 0.10 | 113 | 107 | 0.21 | 23 | 136 | 0 | 290 | 0 | 0.97 | 411 |
| **13** | | 1082 | 0.11 | 117 | 107 | 0.22 | 24 | 140 | 0 | 290 | 0 | 0.96 | 415 |
| **14** | | 1082 | 0.11 | 121 | 107 | 0.22 | 24 | 145 | 0 | 290 | 0 | 0.96 | 419 |
| **15** | | 1082 | 0.12 | 126 | 107 | 0.23 | 25 | 150 | 196 | 290 | 0 | 0.92 | 586 |
| **16** | | 1082 | 0.12 | 131 | 107 | 0.23 | 25 | 156 | 0 | 290 | 0 | 0.92 | 408 |
| **17** | | 1082 | 0.13 | 136 | 107 | 0.24 | 26 | 161 | 0 | 290 | 0 | 0.91 | 411 |
| **18** | | 1082 | 0.13 | 141 | 107 | 0.24 | 26 | 167 | 0 | 290 | 0 | 0.91 | 414 |
| **19** | | 1082 | 0.14 | 146 | 107 | 0.25 | 27 | 173 | 0 | 290 | 0 | 0.90 | 417 |
| **20** | | 1082 | 0.14 | 152 | 107 | 0.26 | 27 | 179 | 2900 | 290 | 0 | 0.85 | 2849 |
| **21** | | 1082 | 0.15 | 157 | 107 | 0.26 | 28 | 185 | 0 | 290 | 0 | 0.84 | 399 |
| **22** | | 1082 | 0.15 | 163 | 107 | 0.27 | 29 | 192 | 0 | 290 | 0 | 0.83 | 401 |
| **23** | | 1082 | 0.16 | 170 | 107 | 0.27 | 29 | 199 | 0 | 290 | 0 | 0.82 | 403 |
| **24** | | 1082 | 0.16 | 176 | 107 | 0.28 | 30 | 206 | 0 | 290 | 0 | 0.82 | 406 |
| **25** | | 1082 | 0.17 | 183 | 107 | 0.28 | 31 | 213 | 0 | 290 | 0 | 0.80 | 402 |
| **26** | | 1082 | 0.18 | 190 | 107 | 0.29 | 31 | 221 | 0 | 290 | 0 | 0.79 | 405 |
| **27** | | 1082 | 0.18 | 197 | 107 | 0.30 | 32 | 229 | 0 | 290 | 0 | 0.79 | 407 |
| **28** | | 1082 | 0.19 | 204 | 107 | 0.30 | 33 | 237 | 0 | 290 | 0 | 0.78 | 410 |
| **29** | | 1082 | 0.20 | 212 | 107 | 0.31 | 33 | 245 | 0 | 290 | 0 | 0.77 | 413 |
| **30** | | 1082 | 0 | 220 | 107 | 0.32 | 34 | 254 | | 290 | 1375 | 0.76 | -635 |
| **Total** | 9,483 | 32,455 | 4 | 4,049 | 3,219 | 7 | 759 | 4,808 | 3,096 | 8,700 | 1,375 | 28 | 23,208 |

**Case 31**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 10,063 | | | | | | | | | | | | 10,063 |
| **1** | | 1102 | 0.07 | 76 | 93 | 0.17 | 16 | 92 | 0 | 330 | 0 | 1.00 | 422 |
| **2** | | 1102 | 0.07 | 79 | 93 | 0.17 | 16 | 95 | 0 | 330 | 0 | 1.00 | 425 |
| **3** | | 1102 | 0.07 | 82 | 93 | 0.18 | 16 | 98 | 0 | 330 | 0 | 1.00 | 428 |
| **4** | | 1102 | 0.08 | 85 | 93 | 0.18 | 17 | 102 | 0 | 330 | 0 | 1.00 | 432 |
| **5** | | 1102 | 0.08 | 88 | 93 | 0.18 | 17 | 105 | 0 | 330 | 0 | 1.00 | 435 |
| **6** | | 1102 | 0.08 | 92 | 93 | 0.19 | 18 | 109 | 0 | 330 | 0 | 1.00 | 439 |
| **7** | | 1102 | 0.09 | 95 | 93 | 0.19 | 18 | 113 | 0 | 330 | 0 | 1.00 | 443 |
| **8** | | 1102 | 0.09 | 99 | 93 | 0.20 | 18 | 117 | 0 | 330 | 0 | 1.00 | 447 |
| **9** | | 1102 | 0.09 | 102 | 93 | 0.20 | 19 | 121 | 0 | 330 | 0 | 1.00 | 451 |
| **10** | | 1102 | 0.10 | 106 | 93 | 0.21 | 19 | 126 | 0 | 330 | 0 | 0.97 | 443 |
| **11** | | 1102 | 0.10 | 110 | 93 | 0.21 | 20 | 130 | 0 | 330 | 0 | 0.97 | 446 |
| **12** | | 1102 | 0.10 | 115 | 93 | 0.21 | 20 | 135 | 0 | 330 | 0 | 0.97 | 449 |
| **13** | | 1102 | 0.11 | 119 | 93 | 0.22 | 20 | 139 | 0 | 330 | 0 | 0.96 | 453 |
| **14** | | 1102 | 0.11 | 123 | 93 | 0.22 | 21 | 144 | 0 | 330 | 0 | 0.96 | 456 |
| **15** | | 1102 | 0.12 | 128 | 93 | 0.23 | 21 | 150 | 196 | 330 | 0 | 0.92 | 622 |
| **16** | | 1102 | 0.12 | 133 | 93 | 0.23 | 22 | 155 | 0 | 330 | 0 | 0.92 | 444 |
| **17** | | 1102 | 0.13 | 138 | 93 | 0.24 | 22 | 160 | 0 | 330 | 0 | 0.91 | 447 |
| **18** | | 1102 | 0.13 | 143 | 93 | 0.24 | 23 | 166 | 0 | 330 | 0 | 0.91 | 449 |
| **19** | | 1102 | 0.14 | 149 | 93 | 0.25 | 23 | 172 | 0 | 330 | 0 | 0.90 | 452 |
| **20** | | 1102 | 0.14 | 154 | 93 | 0.26 | 24 | 178 | 3900 | 330 | 0 | 0.85 | 3728 |
| **21** | | 1102 | 0.15 | 160 | 93 | 0.26 | 24 | 185 | 0 | 330 | 0 | 0.84 | 432 |
| **22** | | 1102 | 0.15 | 166 | 93 | 0.27 | 25 | 191 | 0 | 330 | 0 | 0.83 | 433 |
| **23** | | 1102 | 0.16 | 173 | 93 | 0.27 | 25 | 198 | 0 | 330 | 0 | 0.82 | 435 |
| **24** | | 1102 | 0.16 | 179 | 93 | 0.28 | 26 | 205 | 0 | 330 | 0 | 0.82 | 438 |
| **25** | | 1102 | 0.17 | 186 | 93 | 0.28 | 26 | 213 | 0 | 330 | 0 | 0.80 | 434 |
| **26** | | 1102 | 0.18 | 193 | 93 | 0.29 | 27 | 220 | 0 | 330 | 0 | 0.79 | 436 |
| **27** | | 1102 | 0.18 | 201 | 93 | 0.30 | 28 | 228 | 0 | 330 | 0 | 0.79 | 438 |
| **28** | | 1102 | 0.19 | 208 | 93 | 0.30 | 28 | 236 | 0 | 330 | 0 | 0.78 | 441 |
| **29** | | 1102 | 0.20 | 216 | 93 | 0.31 | 29 | 245 | 0 | 330 | 0 | 0.77 | 443 |
| **30** | | 1102 | 0.20 | 224 | 93 | 0.32 | 30 | 254 | | 330 | 1620 | 0.76 | -792 |
| **Total** | 10,063 | 33,065 | 4 | 4,126 | 2,792 | 7 | 658 | 4,784 | 4,096 | 9,900 | 1,620 | 28 | 25,513 |

**Case 32**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 10,483 | | | | | | | | | | | | 10,483 |
| **1** | | 1069 | 0.07 | 74 | 90 | 0.17 | 15 | 89 | 0 | 330 | 0 | 1.00 | 419 |
| **2** | | 1069 | 0.07 | 77 | 90 | 0.17 | 16 | 92 | 0 | 330 | 0 | 1.00 | 422 |
| **3** | | 1069 | 0.07 | 79 | 90 | 0.18 | 16 | 95 | 0 | 330 | 0 | 1.00 | 425 |
| **4** | | 1069 | 0.08 | 83 | 90 | 0.18 | 16 | 99 | 0 | 330 | 0 | 1.00 | 429 |
| **5** | | 1069 | 0.08 | 86 | 90 | 0.18 | 17 | 102 | 0 | 330 | 0 | 1.00 | 432 |
| **6** | | 1069 | 0.08 | 89 | 90 | 0.19 | 17 | 106 | 0 | 330 | 0 | 1.00 | 436 |
| **7** | | 1069 | 0.09 | 92 | 90 | 0.19 | 17 | 110 | 0 | 330 | 0 | 1.00 | 440 |
| **8** | | 1069 | 0.09 | 96 | 90 | 0.20 | 18 | 114 | 0 | 330 | 0 | 1.00 | 444 |
| **9** | | 1069 | 0.09 | 99 | 90 | 0.20 | 18 | 118 | 0 | 330 | 0 | 1.00 | 448 |
| **10** | | 1069 | 0.10 | 103 | 90 | 0.21 | 19 | 122 | 0 | 330 | 0 | 0.97 | 439 |
| **11** | | 1069 | 0.10 | 107 | 90 | 0.21 | 19 | 126 | 0 | 330 | 0 | 0.97 | 442 |
| **12** | | 1069 | 0.10 | 111 | 90 | 0.21 | 19 | 131 | 0 | 330 | 0 | 0.97 | 445 |
| **13** | | 1069 | 0.11 | 115 | 90 | 0.22 | 20 | 135 | 0 | 330 | 0 | 0.96 | 449 |
| **14** | | 1069 | 0.11 | 120 | 90 | 0.22 | 20 | 140 | 0 | 330 | 0 | 0.96 | 452 |
| **15** | | 1069 | 0.12 | 124 | 90 | 0.23 | 21 | 145 | 196 | 330 | 0 | 0.92 | 618 |
| **16** | | 1069 | 0.12 | 129 | 90 | 0.23 | 21 | 150 | 0 | 330 | 0 | 0.92 | 440 |
| **17** | | 1069 | 0.13 | 134 | 90 | 0.24 | 22 | 156 | 0 | 330 | 0 | 0.91 | 442 |
| **18** | | 1069 | 0.13 | 139 | 90 | 0.24 | 22 | 161 | 0 | 330 | 0 | 0.91 | 445 |
| **19** | | 1069 | 0.14 | 144 | 90 | 0.25 | 23 | 167 | 0 | 330 | 0 | 0.90 | 448 |
| **20** | | 1069 | 0.14 | 150 | 90 | 0.26 | 23 | 173 | 3900 | 330 | 0 | 0.85 | 3723 |
| **21** | | 1069 | 0.15 | 156 | 90 | 0.26 | 24 | 179 | 0 | 330 | 0 | 0.84 | 427 |
| **22** | | 1069 | 0.15 | 161 | 90 | 0.27 | 24 | 186 | 0 | 330 | 0 | 0.83 | 429 |
| **23** | | 1069 | 0.16 | 168 | 90 | 0.27 | 25 | 192 | 0 | 330 | 0 | 0.82 | 431 |
| **24** | | 1069 | 0.16 | 174 | 90 | 0.28 | 25 | 199 | 0 | 330 | 0 | 0.82 | 433 |
| **25** | | 1069 | 0.17 | 181 | 90 | 0.28 | 26 | 206 | 0 | 330 | 0 | 0.80 | 429 |
| **26** | | 1069 | 0.18 | 187 | 90 | 0.29 | 26 | 214 | 0 | 330 | 0 | 0.79 | 431 |
| **27** | | 1069 | 0.18 | 195 | 90 | 0.30 | 27 | 221 | 0 | 330 | 0 | 0.79 | 433 |
| **28** | | 1069 | 0.19 | 202 | 90 | 0.30 | 27 | 229 | 0 | 330 | 0 | 0.78 | 435 |
| **29** | | 1069 | 0.20 | 210 | 90 | 0.31 | 28 | 238 | 0 | 330 | 0 | 0.77 | 438 |
| **30** | | 1069 | 0.20 | 218 | 90 | 0.32 | 29 | 246 | | 330 | 1620 | 0.76 | -798 |
| **Total** | 10,483 | 32,080 | 4 | 4,003 | 2,709 | 7 | 639 | 4,641 | 4,096 | 9,900 | 1,620 | 28 | 25,808 |

**Case 33**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 14,043 | | | | | | | | | | | | 14,043 |
| **1** | | 1139 | 0.07 | 79 | 94 | 0.17 | 16 | 94 | 0 | 240 | 0 | 1.00 | 334 |
| **2** | | 1139 | 0.07 | 82 | 94 | 0.17 | 16 | 98 | 0 | 240 | 0 | 1.00 | 338 |
| **3** | | 1139 | 0.07 | 85 | 94 | 0.18 | 17 | 101 | 0 | 240 | 0 | 1.00 | 341 |
| **4** | | 1139 | 0.08 | 88 | 94 | 0.18 | 17 | 105 | 0 | 240 | 0 | 1.00 | 345 |
| **5** | | 1139 | 0.08 | 91 | 94 | 0.18 | 17 | 108 | 0 | 240 | 0 | 1.00 | 348 |
| **6** | | 1139 | 0.08 | 95 | 94 | 0.19 | 18 | 112 | 0 | 240 | 0 | 1.00 | 352 |
| **7** | | 1139 | 0.09 | 98 | 94 | 0.19 | 18 | 116 | 0 | 240 | 0 | 1.00 | 356 |
| **8** | | 1139 | 0.09 | 102 | 94 | 0.20 | 18 | 120 | 0 | 240 | 0 | 1.00 | 360 |
| **9** | | 1139 | 0.09 | 106 | 94 | 0.20 | 19 | 125 | 0 | 240 | 0 | 1.00 | 365 |
| **10** | | 1139 | 0.10 | 110 | 94 | 0.21 | 19 | 129 | 0 | 240 | 0 | 0.97 | 359 |
| **11** | | 1139 | 0.10 | 114 | 94 | 0.21 | 20 | 134 | 0 | 240 | 0 | 0.97 | 362 |
| **12** | | 1139 | 0.10 | 118 | 94 | 0.21 | 20 | 139 | 0 | 240 | 0 | 0.97 | 366 |
| **13** | | 1139 | 0.11 | 123 | 94 | 0.22 | 21 | 143 | 0 | 240 | 0 | 0.96 | 370 |
| **14** | | 1139 | 0.11 | 128 | 94 | 0.22 | 21 | 149 | 0 | 240 | 0 | 0.96 | 374 |
| **15** | | 1139 | 0.12 | 132 | 94 | 0.23 | 21 | 154 | 196 | 240 | 0 | 0.92 | 543 |
| **16** | | 1139 | 0.12 | 137 | 94 | 0.23 | 22 | 159 | 0 | 240 | 0 | 0.92 | 366 |
| **17** | | 1139 | 0.13 | 143 | 94 | 0.24 | 22 | 165 | 0 | 240 | 0 | 0.91 | 369 |
| **18** | | 1139 | 0.13 | 148 | 94 | 0.24 | 23 | 171 | 0 | 240 | 0 | 0.91 | 372 |
| **19** | | 1139 | 0.14 | 154 | 94 | 0.25 | 23 | 177 | 0 | 240 | 0 | 0.90 | 376 |
| **20** | | 1139 | 0.14 | 160 | 94 | 0.26 | 24 | 184 | 2900 | 240 | 0 | 0.85 | 2810 |
| **21** | | 1139 | 0.15 | 166 | 94 | 0.26 | 24 | 190 | 0 | 240 | 0 | 0.84 | 361 |
| **22** | | 1139 | 0.15 | 172 | 94 | 0.27 | 25 | 197 | 0 | 240 | 0 | 0.83 | 363 |
| **23** | | 1139 | 0.16 | 179 | 94 | 0.27 | 26 | 204 | 0 | 240 | 0 | 0.82 | 366 |
| **24** | | 1139 | 0.16 | 185 | 94 | 0.28 | 26 | 211 | 0 | 240 | 0 | 0.82 | 369 |
| **25** | | 1139 | 0.17 | 192 | 94 | 0.28 | 27 | 219 | 0 | 240 | 0 | 0.80 | 367 |
| **26** | | 1139 | 0.18 | 200 | 94 | 0.29 | 27 | 227 | 0 | 240 | 0 | 0.79 | 370 |
| **27** | | 1139 | 0.18 | 207 | 94 | 0.30 | 28 | 235 | 0 | 240 | 0 | 0.79 | 373 |
| **28** | | 1139 | 0.19 | 215 | 94 | 0.30 | 28 | 244 | 0 | 240 | 0 | 0.78 | 376 |
| **29** | | 1139 | 0.20 | 223 | 94 | 0.31 | 29 | 252 | 0 | 240 | 0 | 0.77 | 380 |
| **30** | | 1139 | 0.20 | 232 | 94 | 0.32 | 30 | 261 | 0 | 240 | 1375 | 0.76 | -668 |
| **Total** | 14,043 | 34,167 | 4 | 4,263 | 2,809 | 7 | 662 | 4,925 | 3,096 | 7,200 | 1,375 | 28 | 26,508 |

**Case 34**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 14,463 | | | | | | | | | | | | 14,463 |
| **1** | | 1106 | 0.07 | 76 | 90 | 0.17 | 15 | 92 | 0 | 240 | 0 | 1.00 | 332 |
| **2** | | 1106 | 0.07 | 79 | 90 | 0.17 | 16 | 95 | 0 | 240 | 0 | 1.00 | 335 |
| **3** | | 1106 | 0.07 | 82 | 90 | 0.18 | 16 | 98 | 0 | 240 | 0 | 1.00 | 338 |
| **4** | | 1106 | 0.08 | 85 | 90 | 0.18 | 16 | 102 | 0 | 240 | 0 | 1.00 | 342 |
| **5** | | 1106 | 0.08 | 89 | 90 | 0.18 | 17 | 105 | 0 | 240 | 0 | 1.00 | 345 |
| **6** | | 1106 | 0.08 | 92 | 90 | 0.19 | 17 | 109 | 0 | 240 | 0 | 1.00 | 349 |
| **7** | | 1106 | 0.09 | 95 | 90 | 0.19 | 17 | 113 | 0 | 240 | 0 | 1.00 | 353 |
| **8** | | 1106 | 0.09 | 99 | 90 | 0.20 | 18 | 117 | 0 | 240 | 0 | 1.00 | 357 |
| **9** | | 1106 | 0.09 | 103 | 90 | 0.20 | 18 | 121 | 0 | 240 | 0 | 1.00 | 361 |
| **10** | | 1106 | 0.10 | 107 | 90 | 0.21 | 19 | 125 | 0 | 240 | 0 | 0.97 | 355 |
| **11** | | 1106 | 0.10 | 111 | 90 | 0.21 | 19 | 130 | 0 | 240 | 0 | 0.97 | 359 |
| **12** | | 1106 | 0.10 | 115 | 90 | 0.21 | 19 | 134 | 0 | 240 | 0 | 0.97 | 362 |
| **13** | | 1106 | 0.11 | 119 | 90 | 0.22 | 20 | 139 | 0 | 240 | 0 | 0.96 | 366 |
| **14** | | 1106 | 0.11 | 124 | 90 | 0.22 | 20 | 144 | 0 | 240 | 0 | 0.96 | 369 |
| **15** | | 1106 | 0.12 | 129 | 90 | 0.23 | 21 | 149 | 196 | 240 | 0 | 0.92 | 539 |
| **16** | | 1106 | 0.12 | 134 | 90 | 0.23 | 21 | 155 | 0 | 240 | 0 | 0.92 | 362 |
| **17** | | 1106 | 0.13 | 139 | 90 | 0.24 | 22 | 160 | 0 | 240 | 0 | 0.91 | 365 |
| **18** | | 1106 | 0.13 | 144 | 90 | 0.24 | 22 | 166 | 0 | 240 | 0 | 0.91 | 368 |
| **19** | | 1106 | 0.14 | 149 | 90 | 0.25 | 23 | 172 | 0 | 240 | 0 | 0.90 | 371 |
| **20** | | 1106 | 0.14 | 155 | 90 | 0.26 | 23 | 178 | 2900 | 240 | 0 | 0.85 | 2806 |
| **21** | | 1106 | 0.15 | 161 | 90 | 0.26 | 24 | 184 | 0 | 240 | 0 | 0.84 | 356 |
| **22** | | 1106 | 0.15 | 167 | 90 | 0.27 | 24 | 191 | 0 | 240 | 0 | 0.83 | 359 |
| **23** | | 1106 | 0.16 | 173 | 90 | 0.27 | 25 | 198 | 0 | 240 | 0 | 0.82 | 361 |
| **24** | | 1106 | 0.16 | 180 | 90 | 0.28 | 25 | 205 | 0 | 240 | 0 | 0.82 | 364 |
| **25** | | 1106 | 0.17 | 187 | 90 | 0.28 | 26 | 213 | 0 | 240 | 0 | 0.80 | 362 |
| **26** | | 1106 | 0.18 | 194 | 90 | 0.29 | 26 | 220 | 0 | 240 | 0 | 0.79 | 365 |
| **27** | | 1106 | 0.18 | 201 | 90 | 0.30 | 27 | 228 | 0 | 240 | 0 | 0.79 | 368 |
| **28** | | 1106 | 0.19 | 209 | 90 | 0.30 | 27 | 236 | 0 | 240 | 0 | 0.78 | 371 |
| **29** | | 1106 | 0.20 | 217 | 90 | 0.31 | 28 | 245 | 0 | 240 | 0 | 0.77 | 374 |
| **30** | | 1106 | 0.20 | 225 | 90 | 0.32 | 29 | 254 | 0 | 240 | 1375 | 0.76 | -674 |
| **Total** | 14,463 | 33,192 | 4 | 4,141 | 2,705 | 7 | 638 | 4,779 | 3,096 | 7,200 | 1,375 | 28 | 26,799 |

**Case 35**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 14,945 | | | | | | | | | | | | 14,945 |
| **1** | | 1144 | 0.07 | 79 | 78 | 0.17 | 13 | 92 | 0 | 280 | 0 | 1.00 | 372 |
| **2** | | 1144 | 0.07 | 82 | 78 | 0.17 | 14 | 95 | 0 | 280 | 0 | 1.00 | 375 |
| **3** | | 1144 | 0.07 | 85 | 78 | 0.18 | 14 | 99 | 0 | 280 | 0 | 1.00 | 379 |
| **4** | | 1144 | 0.08 | 88 | 78 | 0.18 | 14 | 102 | 0 | 280 | 0 | 1.00 | 382 |
| **5** | | 1144 | 0.08 | 92 | 78 | 0.18 | 14 | 106 | 0 | 280 | 0 | 1.00 | 386 |
| **6** | | 1144 | 0.08 | 95 | 78 | 0.19 | 15 | 110 | 0 | 280 | 0 | 1.00 | 390 |
| **7** | | 1144 | 0.09 | 99 | 78 | 0.19 | 15 | 114 | 0 | 280 | 0 | 1.00 | 394 |
| **8** | | 1144 | 0.09 | 102 | 78 | 0.20 | 15 | 118 | 0 | 280 | 0 | 1.00 | 398 |
| **9** | | 1144 | 0.09 | 106 | 78 | 0.20 | 16 | 122 | 0 | 280 | 0 | 1.00 | 402 |
| **10** | | 1144 | 0.10 | 110 | 78 | 0.21 | 16 | 127 | 0 | 280 | 0 | 0.97 | 395 |
| **11** | | 1144 | 0.10 | 115 | 78 | 0.21 | 16 | 131 | 0 | 280 | 0 | 0.97 | 399 |
| **12** | | 1144 | 0.10 | 119 | 78 | 0.21 | 17 | 136 | 0 | 280 | 0 | 0.97 | 402 |
| **13** | | 1144 | 0.11 | 123 | 78 | 0.22 | 17 | 141 | 0 | 280 | 0 | 0.96 | 406 |
| **14** | | 1144 | 0.11 | 128 | 78 | 0.22 | 18 | 146 | 0 | 280 | 0 | 0.96 | 409 |
| **15** | | 1144 | 0.12 | 133 | 78 | 0.23 | 18 | 151 | 196 | 280 | 0 | 0.92 | 577 |
| **16** | | 1144 | 0.12 | 138 | 78 | 0.23 | 18 | 156 | 0 | 280 | 0 | 0.92 | 400 |
| **17** | | 1144 | 0.13 | 143 | 78 | 0.24 | 19 | 162 | 0 | 280 | 0 | 0.91 | 403 |
| **18** | | 1144 | 0.13 | 149 | 78 | 0.24 | 19 | 168 | 0 | 280 | 0 | 0.91 | 406 |
| **19** | | 1144 | 0.14 | 154 | 78 | 0.25 | 20 | 174 | 0 | 280 | 0 | 0.90 | 409 |
| **20** | | 1144 | 0.14 | 160 | 78 | 0.26 | 20 | 180 | 3900 | 280 | 0 | 0.85 | 3687 |
| **21** | | 1144 | 0.15 | 166 | 78 | 0.26 | 20 | 187 | 0 | 280 | 0 | 0.84 | 392 |
| **22** | | 1144 | 0.15 | 173 | 78 | 0.27 | 21 | 194 | 0 | 280 | 0 | 0.83 | 394 |
| **23** | | 1144 | 0.16 | 179 | 78 | 0.27 | 21 | 201 | 0 | 280 | 0 | 0.82 | 396 |
| **24** | | 1144 | 0.16 | 186 | 78 | 0.28 | 22 | 208 | 0 | 280 | 0 | 0.82 | 399 |
| **25** | | 1144 | 0.17 | 193 | 78 | 0.28 | 22 | 216 | 0 | 280 | 0 | 0.80 | 396 |
| **26** | | 1144 | 0.18 | 201 | 78 | 0.29 | 23 | 223 | 0 | 280 | 0 | 0.79 | 399 |
| **27** | | 1144 | 0.18 | 208 | 78 | 0.30 | 23 | 231 | 0 | 280 | 0 | 0.79 | 402 |
| **28** | | 1144 | 0.19 | 216 | 78 | 0.30 | 24 | 240 | 0 | 280 | 0 | 0.78 | 405 |
| **29** | | 1144 | 0.20 | 224 | 78 | 0.31 | 24 | 249 | 0 | 280 | 0 | 0.77 | 408 |
| **30** | | 1144 | 0.20 | 233 | 78 | 0.32 | 25 | 258 | 0 | 280 | 1620 | 0.76 | -827 |
| **Total** | 14,945 | 34,317 | 4 | 4,282 | 2,352 | 7 | 554 | 4,836 | 4,096 | 8,400 | 1,620 | 28 | 29,079 |

**Case 36**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 15,043 | | | | | | | | | | | | 15,043 |
| **1** | | 1126 | 0.07 | 78 | 78 | 0.17 | 13 | 91 | 0 | 280 | 0 | 1.00 | 371 |
| **2** | | 1126 | 0.07 | 81 | 78 | 0.17 | 13 | 94 | 0 | 280 | 0 | 1.00 | 374 |
| **3** | | 1126 | 0.07 | 84 | 78 | 0.18 | 14 | 98 | 0 | 280 | 0 | 1.00 | 378 |
| **4** | | 1126 | 0.08 | 87 | 78 | 0.18 | 14 | 101 | 0 | 280 | 0 | 1.00 | 381 |
| **5** | | 1126 | 0.08 | 90 | 78 | 0.18 | 14 | 105 | 0 | 280 | 0 | 1.00 | 385 |
| **6** | | 1126 | 0.08 | 94 | 78 | 0.19 | 15 | 108 | 0 | 280 | 0 | 1.00 | 388 |
| **7** | | 1126 | 0.09 | 97 | 78 | 0.19 | 15 | 112 | 0 | 280 | 0 | 1.00 | 392 |
| **8** | | 1126 | 0.09 | 101 | 78 | 0.20 | 15 | 116 | 0 | 280 | 0 | 1.00 | 396 |
| **9** | | 1126 | 0.09 | 105 | 78 | 0.20 | 16 | 120 | 0 | 280 | 0 | 1.00 | 400 |
| **10** | | 1126 | 0.10 | 109 | 78 | 0.21 | 16 | 125 | 0 | 280 | 0 | 0.97 | 394 |
| **11** | | 1126 | 0.10 | 113 | 78 | 0.21 | 16 | 129 | 0 | 280 | 0 | 0.97 | 397 |
| **12** | | 1126 | 0.10 | 117 | 78 | 0.21 | 17 | 134 | 0 | 280 | 0 | 0.97 | 400 |
| **13** | | 1126 | 0.11 | 122 | 78 | 0.22 | 17 | 139 | 0 | 280 | 0 | 0.96 | 404 |
| **14** | | 1126 | 0.11 | 126 | 78 | 0.22 | 18 | 144 | 0 | 280 | 0 | 0.96 | 407 |
| **15** | | 1126 | 0.12 | 131 | 78 | 0.23 | 18 | 149 | 196 | 280 | 0 | 0.92 | 575 |
| **16** | | 1126 | 0.12 | 136 | 78 | 0.23 | 18 | 154 | 0 | 280 | 0 | 0.92 | 398 |
| **17** | | 1126 | 0.13 | 141 | 78 | 0.24 | 19 | 160 | 0 | 280 | 0 | 0.91 | 401 |
| **18** | | 1126 | 0.13 | 147 | 78 | 0.24 | 19 | 166 | 0 | 280 | 0 | 0.91 | 404 |
| **19** | | 1126 | 0.14 | 152 | 78 | 0.25 | 20 | 172 | 0 | 280 | 0 | 0.90 | 407 |
| **20** | | 1126 | 0.14 | 158 | 78 | 0.26 | 20 | 178 | 3900 | 280 | 0 | 0.85 | 3685 |
| **21** | | 1126 | 0.15 | 164 | 78 | 0.26 | 20 | 184 | 0 | 280 | 0 | 0.84 | 389 |
| **22** | | 1126 | 0.15 | 170 | 78 | 0.27 | 21 | 191 | 0 | 280 | 0 | 0.83 | 392 |
| **23** | | 1126 | 0.16 | 177 | 78 | 0.27 | 21 | 198 | 0 | 280 | 0 | 0.82 | 394 |
| **24** | | 1126 | 0.16 | 183 | 78 | 0.28 | 22 | 205 | 0 | 280 | 0 | 0.82 | 397 |
| **25** | | 1126 | 0.17 | 190 | 78 | 0.28 | 22 | 212 | 0 | 280 | 0 | 0.80 | 394 |
| **26** | | 1126 | 0.18 | 197 | 78 | 0.29 | 23 | 220 | 0 | 280 | 0 | 0.79 | 396 |
| **27** | | 1126 | 0.18 | 205 | 78 | 0.30 | 23 | 228 | 0 | 280 | 0 | 0.79 | 399 |
| **28** | | 1126 | 0.19 | 213 | 78 | 0.30 | 24 | 236 | 0 | 280 | 0 | 0.78 | 402 |
| **29** | | 1126 | 0.20 | 221 | 78 | 0.31 | 24 | 245 | 0 | 280 | 0 | 0.77 | 405 |
| **30** | | 1126 | 0.20 | 229 | 78 | 0.32 | 25 | 254 | 0 | 280 | 1620 | 0.76 | -830 |
| **Total** | 15,043 | 33,789 | 4 | 4,216 | 2,344 | 7 | 552 | 4,768 | 4,096 | 8,400 | 1,620 | 28 | 29,117 |

**Case 37**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 15,365 | | | | | | | | | | | | 15,365 |
| **1** | | 1112 | 0.07 | 77 | 76 | 0.17 | 13 | 90 | 0 | 280 | 0 | 1.00 | 370 |
| **2** | | 1112 | 0.07 | 80 | 76 | 0.17 | 13 | 93 | 0 | 280 | 0 | 1.00 | 373 |
| **3** | | 1112 | 0.07 | 83 | 76 | 0.18 | 13 | 96 | 0 | 280 | 0 | 1.00 | 376 |
| **4** | | 1112 | 0.08 | 86 | 76 | 0.18 | 14 | 99 | 0 | 280 | 0 | 1.00 | 379 |
| **5** | | 1112 | 0.08 | 89 | 76 | 0.18 | 14 | 103 | 0 | 280 | 0 | 1.00 | 383 |
| **6** | | 1112 | 0.08 | 92 | 76 | 0.19 | 14 | 107 | 0 | 280 | 0 | 1.00 | 387 |
| **7** | | 1112 | 0.09 | 96 | 76 | 0.19 | 15 | 111 | 0 | 280 | 0 | 1.00 | 391 |
| **8** | | 1112 | 0.09 | 100 | 76 | 0.20 | 15 | 114 | 0 | 280 | 0 | 1.00 | 394 |
| **9** | | 1112 | 0.09 | 103 | 76 | 0.20 | 15 | 119 | 0 | 280 | 0 | 1.00 | 399 |
| **10** | | 1112 | 0.10 | 107 | 76 | 0.21 | 16 | 123 | 0 | 280 | 0 | 0.97 | 392 |
| **11** | | 1112 | 0.10 | 111 | 76 | 0.21 | 16 | 127 | 0 | 280 | 0 | 0.97 | 395 |
| **12** | | 1112 | 0.10 | 116 | 76 | 0.21 | 16 | 132 | 0 | 280 | 0 | 0.97 | 398 |
| **13** | | 1112 | 0.11 | 120 | 76 | 0.22 | 17 | 137 | 0 | 280 | 0 | 0.96 | 402 |
| **14** | | 1112 | 0.11 | 125 | 76 | 0.22 | 17 | 142 | 0 | 280 | 0 | 0.96 | 405 |
| **15** | | 1112 | 0.12 | 129 | 76 | 0.23 | 17 | 147 | 196 | 280 | 0 | 0.92 | 573 |
| **16** | | 1112 | 0.12 | 134 | 76 | 0.23 | 18 | 152 | 0 | 280 | 0 | 0.92 | 396 |
| **17** | | 1112 | 0.13 | 139 | 76 | 0.24 | 18 | 157 | 0 | 280 | 0 | 0.91 | 398 |
| **18** | | 1112 | 0.13 | 145 | 76 | 0.24 | 19 | 163 | 0 | 280 | 0 | 0.91 | 401 |
| **19** | | 1112 | 0.14 | 150 | 76 | 0.25 | 19 | 169 | 0 | 280 | 0 | 0.90 | 405 |
| **20** | | 1112 | 0.14 | 156 | 76 | 0.26 | 19 | 175 | 3900 | 280 | 0 | 0.85 | 3683 |
| **21** | | 1112 | 0.15 | 162 | 76 | 0.26 | 20 | 182 | 0 | 280 | 0 | 0.84 | 387 |
| **22** | | 1112 | 0.15 | 168 | 76 | 0.27 | 20 | 188 | 0 | 280 | 0 | 0.83 | 389 |
| **23** | | 1112 | 0.16 | 174 | 76 | 0.27 | 21 | 195 | 0 | 280 | 0 | 0.82 | 392 |
| **24** | | 1112 | 0.16 | 181 | 76 | 0.28 | 21 | 202 | 0 | 280 | 0 | 0.82 | 394 |
| **25** | | 1112 | 0.17 | 188 | 76 | 0.28 | 22 | 209 | 0 | 280 | 0 | 0.80 | 391 |
| **26** | | 1112 | 0.18 | 195 | 76 | 0.29 | 22 | 217 | 0 | 280 | 0 | 0.79 | 394 |
| **27** | | 1112 | 0.18 | 202 | 76 | 0.30 | 23 | 225 | 0 | 280 | 0 | 0.79 | 396 |
| **28** | | 1112 | 0.19 | 210 | 76 | 0.30 | 23 | 233 | 0 | 280 | 0 | 0.78 | 399 |
| **29** | | 1112 | 0.20 | 218 | 76 | 0.31 | 24 | 241 | 0 | 280 | 0 | 0.77 | 402 |
| **30** | | 1112 | 0.20 | 226 | 76 | 0.32 | 24 | 250 | 0 | 280 | 1620 | 0.76 | -833 |
| **Total** | 15,365 | 33,352 | 4 | 4,161 | 2,273 | 7 | 536 | 4,697 | 4,096 | 8,400 | 1,620 | 28 | 29,376 |

**Case 38**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 15,463 | | | | | | | | | | | | 15,463 |
| **1** | | 1094 | 0.07 | 75 | 75 | 0.17 | 13 | 88 | 0 | 280 | 0 | 1.00 | 368 |
| **2** | | 1094 | 0.07 | 78 | 75 | 0.17 | 13 | 91 | 0 | 280 | 0 | 1.00 | 371 |
| **3** | | 1094 | 0.07 | 81 | 75 | 0.18 | 13 | 95 | 0 | 280 | 0 | 1.00 | 375 |
| **4** | | 1094 | 0.08 | 84 | 75 | 0.18 | 14 | 98 | 0 | 280 | 0 | 1.00 | 378 |
| **5** | | 1094 | 0.08 | 88 | 75 | 0.18 | 14 | 102 | 0 | 280 | 0 | 1.00 | 382 |
| **6** | | 1094 | 0.08 | 91 | 75 | 0.19 | 14 | 105 | 0 | 280 | 0 | 1.00 | 385 |
| **7** | | 1094 | 0.09 | 94 | 75 | 0.19 | 15 | 109 | 0 | 280 | 0 | 1.00 | 389 |
| **8** | | 1094 | 0.09 | 98 | 75 | 0.20 | 15 | 113 | 0 | 280 | 0 | 1.00 | 393 |
| **9** | | 1094 | 0.09 | 102 | 75 | 0.20 | 15 | 117 | 0 | 280 | 0 | 1.00 | 397 |
| **10** | | 1094 | 0.10 | 106 | 75 | 0.21 | 16 | 121 | 0 | 280 | 0 | 0.97 | 390 |
| **11** | | 1094 | 0.10 | 110 | 75 | 0.21 | 16 | 125 | 0 | 280 | 0 | 0.97 | 393 |
| **12** | | 1094 | 0.10 | 114 | 75 | 0.21 | 16 | 130 | 0 | 280 | 0 | 0.97 | 396 |
| **13** | | 1094 | 0.11 | 118 | 75 | 0.22 | 17 | 135 | 0 | 280 | 0 | 0.96 | 400 |
| **14** | | 1094 | 0.11 | 123 | 75 | 0.22 | 17 | 140 | 0 | 280 | 0 | 0.96 | 403 |
| **15** | | 1094 | 0.12 | 127 | 75 | 0.23 | 17 | 145 | 196 | 280 | 0 | 0.92 | 571 |
| **16** | | 1094 | 0.12 | 132 | 75 | 0.23 | 18 | 150 | 0 | 280 | 0 | 0.92 | 394 |
| **17** | | 1094 | 0.13 | 137 | 75 | 0.24 | 18 | 155 | 0 | 280 | 0 | 0.91 | 396 |
| **18** | | 1094 | 0.13 | 142 | 75 | 0.24 | 18 | 161 | 0 | 280 | 0 | 0.91 | 399 |
| **19** | | 1094 | 0.14 | 148 | 75 | 0.25 | 19 | 167 | 0 | 280 | 0 | 0.90 | 402 |
| **20** | | 1094 | 0.14 | 153 | 75 | 0.26 | 19 | 173 | 3900 | 280 | 0 | 0.85 | 3681 |
| **21** | | 1094 | 0.15 | 159 | 75 | 0.26 | 20 | 179 | 0 | 280 | 0 | 0.84 | 385 |
| **22** | | 1094 | 0.15 | 165 | 75 | 0.27 | 20 | 185 | 0 | 280 | 0 | 0.83 | 387 |
| **23** | | 1094 | 0.16 | 171 | 75 | 0.27 | 21 | 192 | 0 | 280 | 0 | 0.82 | 389 |
| **24** | | 1094 | 0.16 | 178 | 75 | 0.28 | 21 | 199 | 0 | 280 | 0 | 0.82 | 392 |
| **25** | | 1094 | 0.17 | 185 | 75 | 0.28 | 21 | 206 | 0 | 280 | 0 | 0.80 | 389 |
| **26** | | 1094 | 0.18 | 192 | 75 | 0.29 | 22 | 214 | 0 | 280 | 0 | 0.79 | 391 |
| **27** | | 1094 | 0.18 | 199 | 75 | 0.30 | 22 | 222 | 0 | 280 | 0 | 0.79 | 394 |
| **28** | | 1094 | 0.19 | 207 | 75 | 0.30 | 23 | 230 | 0 | 280 | 0 | 0.78 | 397 |
| **29** | | 1094 | 0.20 | 214 | 75 | 0.31 | 23 | 238 | 0 | 280 | 0 | 0.77 | 399 |
| **30** | | 1094 | 0 | 223 | 75 | 0.32 | 24 | 247 | 0 | 280 | 1620 | 0.76 | -836 |
| **Total** | 15,463 | 32,821 | 4 | 4,095 | 2,264 | 7 | 534 | 4,629 | 4,096 | 8,400 | 1,620 | 28 | 29,413 |

| Case 39 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 16,218 | | | | | | | | | | | | 16,218 |
| **1** | | 1141 | 0.07 | 79 | 84 | 0.17 | 14 | 93 | 0 | 371 | 0 | 1.00 | 463 |
| **2** | | 1141 | 0.07 | 82 | 84 | 0.17 | 15 | 96 | 0 | 371 | 0 | 1.00 | 467 |
| **3** | | 1141 | 0.07 | 85 | 84 | 0.18 | 15 | 100 | 0 | 371 | 0 | 1.00 | 470 |
| **4** | | 1141 | 0.08 | 88 | 84 | 0.18 | 15 | 103 | 0 | 371 | 0 | 1.00 | 474 |
| **5** | | 1141 | 0.08 | 91 | 84 | 0.18 | 16 | 107 | 0 | 371 | 0 | 1.00 | 477 |
| **6** | | 1141 | 0.08 | 95 | 84 | 0.19 | 16 | 111 | 0 | 371 | 0 | 1.00 | 481 |
| **7** | | 1141 | 0.09 | 98 | 84 | 0.19 | 16 | 115 | 0 | 371 | 0 | 1.00 | 485 |
| **8** | | 1141 | 0.09 | 102 | 84 | 0.20 | 17 | 119 | 0 | 371 | 0 | 1.00 | 489 |
| **9** | | 1141 | 0.09 | 106 | 84 | 0.20 | 17 | 123 | 0 | 371 | 0 | 1.00 | 493 |
| **10** | | 1141 | 0.10 | 110 | 84 | 0.21 | 17 | 127 | 0 | 371 | 0 | 0.97 | 484 |
| **11** | | 1141 | 0.10 | 114 | 84 | 0.21 | 18 | 132 | 0 | 371 | 0 | 0.97 | 487 |
| **12** | | 1141 | 0.10 | 119 | 84 | 0.21 | 18 | 137 | 0 | 371 | 0 | 0.97 | 490 |
| **13** | | 1141 | 0.11 | 123 | 84 | 0.22 | 18 | 142 | 0 | 371 | 0 | 0.96 | 494 |
| **14** | | 1141 | 0.11 | 128 | 84 | 0.22 | 19 | 147 | 0 | 371 | 0 | 0.96 | 497 |
| **15** | | 1141 | 0.12 | 133 | 84 | 0.23 | 19 | 152 | 196 | 371 | 0 | 0.92 | 661 |
| **16** | | 1141 | 0.12 | 138 | 84 | 0.23 | 20 | 157 | 0 | 371 | 0 | 0.92 | 484 |
| **17** | | 1141 | 0.13 | 143 | 84 | 0.24 | 20 | 163 | 0 | 371 | 0 | 0.91 | 486 |
| **18** | | 1141 | 0.13 | 148 | 84 | 0.24 | 21 | 169 | 0 | 371 | 0 | 0.91 | 489 |
| **19** | | 1141 | 0.14 | 154 | 84 | 0.25 | 21 | 175 | 0 | 371 | 0 | 0.90 | 492 |
| **20** | | 1141 | 0.14 | 160 | 84 | 0.26 | 21 | 181 | 2900 | 371 | 0 | 0.85 | 2919 |
| **21** | | 1141 | 0.15 | 166 | 84 | 0.26 | 22 | 188 | 0 | 371 | 0 | 0.84 | 468 |
| **22** | | 1141 | 0.15 | 172 | 84 | 0.27 | 22 | 195 | 0 | 371 | 0 | 0.83 | 470 |
| **23** | | 1141 | 0.16 | 179 | 84 | 0.27 | 23 | 202 | 0 | 371 | 0 | 0.82 | 472 |
| **24** | | 1141 | 0.16 | 186 | 84 | 0.28 | 23 | 209 | 0 | 371 | 0 | 0.82 | 474 |
| **25** | | 1141 | 0.17 | 193 | 84 | 0.28 | 24 | 217 | 0 | 371 | 0 | 0.80 | 469 |
| **26** | | 1141 | 0.18 | 200 | 84 | 0.29 | 24 | 224 | 0 | 371 | 0 | 0.79 | 471 |
| **27** | | 1141 | 0.18 | 208 | 84 | 0.30 | 25 | 233 | 0 | 371 | 0 | 0.79 | 474 |
| **28** | | 1141 | 0.19 | 215 | 84 | 0.30 | 26 | 241 | 0 | 371 | 0 | 0.78 | 476 |
| **29** | | 1141 | 0.20 | 224 | 84 | 0.31 | 26 | 250 | 0 | 371 | 0 | 0.77 | 478 |
| **30** | | 1141 | 0.20 | 232 | 84 | 0.32 | 27 | 259 | 0 | 371 | 1455 | 0.76 | -631 |
| **Total** | 16,218 | 34,223 | 4 | 4,270 | 2,524 | 7 | 595 | 4,865 | 3,096 | 11,115 | 1,455 | 28 | 32,123 |

| Case 40 | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Year** | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replace ment/Re pair cost (€) | Mainte nance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
| **0** | 17,851 | | | | | | | | | | | | 17,851 |
| **1** | | 885 | 0.07 | 61 | 266 | 0.17 | 45 | 106 | 0 | 240 | 0 | 1.00 | 346 |
| **2** | | 885 | 0.07 | 63 | 266 | 0.17 | 46 | 109 | 0 | 240 | 0 | 1.00 | 349 |
| **3** | | 885 | 0.07 | 66 | 266 | 0.18 | 47 | 113 | 0 | 240 | 0 | 1.00 | 353 |
| **4** | | 885 | 0.08 | 68 | 266 | 0.18 | 48 | 116 | 0 | 240 | 0 | 1.00 | 356 |
| **5** | | 885 | 0.08 | 71 | 266 | 0.18 | 49 | 120 | 0 | 240 | 0 | 1.00 | 360 |
| **6** | | 885 | 0.08 | 74 | 266 | 0.19 | 50 | 124 | 0 | 240 | 0 | 1.00 | 364 |
| **7** | | 885 | 0.09 | 76 | 266 | 0.19 | 51 | 128 | 0 | 240 | 0 | 1.00 | 368 |
| **8** | | 885 | 0.09 | 79 | 266 | 0.20 | 52 | 132 | 0 | 240 | 0 | 1.00 | 372 |
| **9** | | 885 | 0.09 | 82 | 266 | 0.20 | 53 | 136 | 0 | 240 | 0 | 1.00 | 376 |
| **10** | | 885 | 0.10 | 85 | 266 | 0.21 | 55 | 140 | 0 | 240 | 0 | 0.97 | 370 |
| **11** | | 885 | 0.10 | 89 | 266 | 0.21 | 56 | 145 | 0 | 240 | 0 | 0.97 | 373 |
| **12** | | 885 | 0.10 | 92 | 266 | 0.21 | 57 | 149 | 0 | 240 | 0 | 0.97 | 376 |
| **13** | | 885 | 0.11 | 96 | 266 | 0.22 | 58 | 154 | 0 | 240 | 0 | 0.96 | 380 |
| **14** | | 885 | 0.11 | 99 | 266 | 0.22 | 60 | 159 | 0 | 240 | 0 | 0.96 | 383 |
| **15** | | 885 | 0.12 | 103 | 266 | 0.23 | 61 | 164 | 196 | 240 | 0 | 0.92 | 552 |
| **16** | | 885 | 0.12 | 107 | 266 | 0.23 | 62 | 169 | 0 | 240 | 0 | 0.92 | 375 |
| **17** | | 885 | 0.13 | 111 | 266 | 0.24 | 64 | 175 | 0 | 240 | 0 | 0.91 | 378 |
| **18** | | 885 | 0.13 | 115 | 266 | 0.24 | 65 | 180 | 0 | 240 | 0 | 0.91 | 381 |
| **19** | | 885 | 0.14 | 120 | 266 | 0.25 | 66 | 186 | 0 | 240 | 0 | 0.90 | 384 |
| **20** | | 885 | 0.14 | 124 | 266 | 0.26 | 68 | 192 | 2900 | 240 | 0 | 0.85 | 2818 |
| **21** | | 885 | 0.15 | 129 | 266 | 0.26 | 69 | 198 | 0 | 240 | 0 | 0.84 | 367 |
| **22** | | 885 | 0.15 | 134 | 266 | 0.27 | 71 | 205 | 0 | 240 | 0 | 0.83 | 370 |
| **23** | | 885 | 0.16 | 139 | 266 | 0.27 | 72 | 211 | 0 | 240 | 0 | 0.82 | 372 |
| **24** | | 885 | 0.16 | 144 | 266 | 0.28 | 74 | 218 | 0 | 240 | 0 | 0.82 | 375 |
| **25** | | 885 | 0.17 | 150 | 266 | 0.28 | 76 | 225 | 0 | 240 | 0 | 0.80 | 372 |
| **26** | | 885 | 0.18 | 155 | 266 | 0.29 | 77 | 233 | 0 | 240 | 0 | 0.79 | 374 |
| **27** | | 885 | 0.18 | 161 | 266 | 0.30 | 79 | 240 | 0 | 240 | 0 | 0.79 | 377 |
| **28** | | 885 | 0.19 | 167 | 266 | 0.30 | 81 | 248 | 0 | 240 | 0 | 0.78 | 380 |
| **29** | | 885 | 0.20 | 174 | 266 | 0.31 | 83 | 256 | 0 | 240 | 0 | 0.77 | 383 |
| **30** | | 885 | 0.20 | 180 | 266 | 0 | 84 | 265 | 0 | 240 | 1375 | 0.76 | -665 |
| **Total** | 17,851 | 26,563 | 4 | 3,314 | 7,972 | 7 | 1,879 | 5,193 | 3,096 | 7,200 | 1,375 | 28 | 30,566 |

**Case 41**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 21,026 | | | | | | | | | | | | 21,026 |
| **1** | | 875 | 0.07 | 60 | 74 | 0.17 | 13 | 73 | 0 | 411 | 0 | 1.00 | 483 |
| **2** | | 875 | 0.07 | 63 | 74 | 0.17 | 13 | 75 | 0 | 411 | 0 | 1.00 | 486 |
| **3** | | 875 | 0.07 | 65 | 74 | 0.18 | 13 | 78 | 0 | 411 | 0 | 1.00 | 489 |
| **4** | | 875 | 0.08 | 68 | 74 | 0.18 | 13 | 81 | 0 | 411 | 0 | 1.00 | 491 |
| **5** | | 875 | 0.08 | 70 | 74 | 0.18 | 14 | 84 | 0 | 411 | 0 | 1.00 | 494 |
| **6** | | 875 | 0.08 | 73 | 74 | 0.19 | 14 | 87 | 0 | 411 | 0 | 1.00 | 497 |
| **7** | | 875 | 0.09 | 76 | 74 | 0.19 | 14 | 90 | 0 | 411 | 0 | 1.00 | 500 |
| **8** | | 875 | 0.09 | 78 | 74 | 0.20 | 15 | 93 | 0 | 411 | 0 | 1.00 | 503 |
| **9** | | 875 | 0.09 | 81 | 74 | 0.20 | 15 | 96 | 0 | 411 | 0 | 1.00 | 507 |
| **10** | | 875 | 0.10 | 84 | 74 | 0.21 | 15 | 100 | 0 | 411 | 0 | 0.97 | 496 |
| **11** | | 875 | 0.10 | 88 | 74 | 0.21 | 16 | 103 | 0 | 411 | 0 | 0.97 | 498 |
| **12** | | 875 | 0.10 | 91 | 74 | 0.21 | 16 | 107 | 0 | 411 | 0 | 0.97 | 500 |
| **13** | | 875 | 0.11 | 94 | 74 | 0.22 | 16 | 111 | 0 | 411 | 0 | 0.96 | 503 |
| **14** | | 875 | 0.11 | 98 | 74 | 0.22 | 17 | 115 | 0 | 411 | 0 | 0.96 | 505 |
| **15** | | 875 | 0.12 | 102 | 74 | 0.23 | 17 | 119 | 196 | 411 | 0 | 0.92 | 668 |
| **16** | | 875 | 0.12 | 106 | 74 | 0.23 | 17 | 123 | 0 | 411 | 0 | 0.92 | 489 |
| **17** | | 875 | 0.13 | 110 | 74 | 0.24 | 18 | 127 | 0 | 411 | 0 | 0.91 | 490 |
| **18** | | 875 | 0.13 | 114 | 74 | 0.24 | 18 | 132 | 0 | 411 | 0 | 0.91 | 491 |
| **19** | | 875 | 0.14 | 118 | 74 | 0.25 | 19 | 137 | 0 | 411 | 0 | 0.90 | 493 |
| **20** | | 875 | 0.14 | 123 | 74 | 0.26 | 19 | 142 | 3900 | 411 | 0 | 0.85 | 3765 |
| **21** | | 875 | 0.15 | 127 | 74 | 0.26 | 19 | 147 | 0 | 411 | 0 | 0.84 | 467 |
| **22** | | 875 | 0.15 | 132 | 74 | 0.27 | 20 | 152 | 0 | 411 | 0 | 0.83 | 468 |
| **23** | | 875 | 0.16 | 137 | 74 | 0.27 | 20 | 157 | 0 | 411 | 0 | 0.82 | 468 |
| **24** | | 875 | 0.16 | 142 | 74 | 0.28 | 21 | 163 | 0 | 411 | 0 | 0.82 | 469 |
| **25** | | 875 | 0.17 | 148 | 74 | 0.28 | 21 | 169 | 0 | 411 | 0 | 0.80 | 463 |
| **26** | | 875 | 0.18 | 153 | 74 | 0.29 | 22 | 175 | 0 | 411 | 0 | 0.79 | 464 |
| **27** | | 875 | 0.18 | 159 | 74 | 0.30 | 22 | 181 | 0 | 411 | 0 | 0.79 | 465 |
| **28** | | 875 | 0.19 | 165 | 74 | 0.30 | 23 | 188 | 0 | 411 | 0 | 0.78 | 466 |
| **29** | | 875 | 0.20 | 172 | 74 | 0.31 | 23 | 195 | 0 | 411 | 0 | 0.77 | 467 |
| **30** | | 875 | 0.20 | 178 | 74 | 0.32 | 24 | 202 | 0 | 411 | 1700 | 0.76 | -831 |
| **Total** | 21,026 | 26,257 | 4 | 3,276 | 2,225 | 7 | 524 | 3,800 | 4,096 | 12,315 | 1,700 | 28 | 37,740 |

**Case 42**

| Year | Initial Cost (€) | Heating Energy cons. (KWh) | Heating Energy price (€) | Heating Cost energy (€) | Cooling Energy cons. (KWh) | Cooling Energy price (€) | Cooling Cost energy (€) | Total energy cost (€) | Replacement/Repair cost (€) | Maintenance cost (€) | Residual value (€) | Discount Rate | LCCA (Cg) (€) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 21,446 | | | | | | | | | | | | 21,446 |
| **1** | | 839 | 0.07 | 58 | 71 | 0.17 | 12 | 70 | 0 | 411 | 0 | 1.00 | 480 |
| **2** | | 839 | 0.07 | 60 | 71 | 0.17 | 12 | 72 | 0 | 411 | 0 | 1.00 | 483 |
| **3** | | 839 | 0.07 | 62 | 71 | 0.18 | 13 | 75 | 0 | 411 | 0 | 1.00 | 486 |
| **4** | | 839 | 0.08 | 65 | 71 | 0.18 | 13 | 78 | 0 | 411 | 0 | 1.00 | 488 |
| **5** | | 839 | 0.08 | 67 | 71 | 0.18 | 13 | 80 | 0 | 411 | 0 | 1.00 | 491 |
| **6** | | 839 | 0.08 | 70 | 71 | 0.19 | 13 | 83 | 0 | 411 | 0 | 1.00 | 494 |
| **7** | | 839 | 0.09 | 72 | 71 | 0.19 | 14 | 86 | 0 | 411 | 0 | 1.00 | 497 |
| **8** | | 839 | 0.09 | 75 | 71 | 0.20 | 14 | 89 | 0 | 411 | 0 | 1.00 | 500 |
| **9** | | 839 | 0.09 | 78 | 71 | 0.20 | 14 | 92 | 0 | 411 | 0 | 1.00 | 503 |
| **10** | | 839 | 0.10 | 81 | 71 | 0.21 | 15 | 96 | 0 | 411 | 0 | 0.97 | 492 |
| **11** | | 839 | 0.10 | 84 | 71 | 0.21 | 15 | 99 | 0 | 411 | 0 | 0.97 | 494 |
| **12** | | 839 | 0.10 | 87 | 71 | 0.21 | 15 | 103 | 0 | 411 | 0 | 0.97 | 496 |
| **13** | | 839 | 0.11 | 91 | 71 | 0.22 | 16 | 106 | 0 | 411 | 0 | 0.96 | 498 |
| **14** | | 839 | 0.11 | 94 | 71 | 0.22 | 16 | 110 | 0 | 411 | 0 | 0.96 | 501 |
| **15** | | 839 | 0.12 | 98 | 71 | 0.23 | 16 | 114 | | 411 | 0 | 0.92 | 483 |
| **16** | | 839 | 0.12 | 101 | 71 | 0.23 | 17 | 118 | 0 | 411 | 0 | 0.92 | 484 |
| **17** | | 839 | 0.13 | 105 | 71 | 0.24 | 17 | 122 | 0 | 411 | 0 | 0.91 | 485 |
| **18** | | 839 | 0.13 | 109 | 71 | 0.24 | 17 | 127 | 0 | 411 | 0 | 0.91 | 487 |
| **19** | | 839 | 0.14 | 113 | 71 | 0.25 | 18 | 131 | 0 | 411 | 0 | 0.90 | 488 |
| **20** | | 839 | 0.14 | 118 | 71 | 0.26 | 18 | 136 | 3900 | 411 | 0 | 0.85 | 3760 |
| **21** | | 839 | 0.15 | 122 | 71 | 0.26 | 19 | 141 | 0 | 411 | 0 | 0.84 | 462 |
| **22** | | 839 | 0.15 | 127 | 71 | 0.27 | 19 | 146 | 0 | 411 | 0 | 0.83 | 463 |
| **23** | | 839 | 0.16 | 132 | 71 | 0.27 | 19 | 151 | 0 | 411 | 0 | 0.82 | 463 |
| **24** | | 839 | 0.16 | 137 | 71 | 0.28 | 20 | 156 | 0 | 411 | 0 | 0.82 | 464 |
| **25** | | 839 | 0.17 | 142 | 71 | 0.28 | 20 | 162 | 0 | 411 | 0 | 0.80 | 458 |
| **26** | | 839 | 0.18 | 147 | 71 | 0.29 | 21 | 168 | 0 | 411 | 0 | 0.79 | 458 |
| **27** | | 839 | 0.18 | 153 | 71 | 0.30 | 21 | 174 | 0 | 411 | 0 | 0.79 | 459 |
| **28** | | 839 | 0.19 | 159 | 71 | 0.30 | 22 | 180 | 0 | 411 | 0 | 0.78 | 460 |
| **29** | | 839 | 0.20 | 165 | 71 | 0.31 | 22 | 187 | 0 | 411 | 0 | 0.77 | 461 |
| **30** | | 839 | 0.20 | 171 | 71 | 0.32 | 23 | 194 | 0 | 411 | 1700 | 0.76 | -838 |
| **Total** | 21,446 | 25,184 | 4 | 3,142 | 2,144 | 7 | 505 | 3,648 | 3,900 | 12,315 | 1,700 | 28 | 37,845 |