UNIVERSITY OF CYPRUS

FACULTY OF ENGINEERING

DEPARTMENT OF ARCHITECTURE

« Building Integration of a BIPV and a BIPV/T System on a Double Skin Façade: Design Optimization and Energy Analysis of a One-Bedroom Studio Apartment and its Semi-Open Space. »

M.Sc. DISSERTATION

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NICOSIA

JANUARY 2022

UNIVERSITY OF CYPRUS

FACULTY OF ENGINEERING, DEPARTMENT OF ARCHITECTURE

BUILDING INTEGRATION OF A BIPV AND A BIPV/T SYSTEM ON A DOUBLE SKIN FAÇADE: *DESIGN OPTIMIZATION AND ENERGY ANALYSIS OF A ONE-BEDROOM STUDIO APARTMENT AND ITS SEMI-OPEN SPACE.*

M.Sc. Dissertation

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MASTER OF SCIENCE
INTER-DEPARTMENTAL PROGRAM
«ENERGY TECHNOLOGIES AND SUSTAINABLE DESIGN»

Nicosia, January 2022

Dedicated to my Family

UNIVERSITY OF CYPRUS
FACULTY OF ENGINEERING
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Building Integration of a BIPV and a BIPV/T System on a Double Skin Façade:
Design Optimization and Energy Analysis of a One-Bedroom Studio Apartment and its Semi-Open Space.

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Abstract

1 ABSTRACT

The improvement of the energy performance of buildings, alongside the utilization of alternative energy sources is imperative these days since the building sector in Europe accounts for a significant amount of GHG emissions and 40% of the primary energy needs. Given that the development of multi-storey housing complexes continues, the building integration of passive techniques and active solar systems emerge as an energy-saving solution and a green construction practice, which is directly linked to the reduction of the environmental impact. During the last years, designers searched for new ways of optimizing the energy performance of multi-storey buildings, and one of them was improving the standard building façade envelope by introducing a Double Façade system. Through the implementation of Double Façade systems, Architects and Engineers can implement a system where natural ventilation can occur, maximize, and control the amount of natural light entering the internal spaces, provide shading and protect the building against wind loads, moisture, overheating and cooling loads. Apart from the standard Double Façade systems, there is also an increasing interest in Photovoltaic panels and more specifically the integration of PV panels these being Building Integrated Photovoltaic Panels (BIPV) or Building Integrated Photovoltaic Panels/Thermal (BIPV/T). The difference between the two is that with the use of BIPV/Ts, the heat emitted from the PVs is collected and transformed into thermal energy.

This research investigates the contribution of three proposed double façade systems, a Conventional Double Façade (DF) system, a BIPV DF system and a BIPV/T DF system, on a one-bedroom studio housing module in terms of energy production, thermal loads and primary energy demands for heating and cooling. The cavity space of the DF system is treated as a “veranda”, a semi-open space which acts as an extension of the living space. Firstly, the module’s characteristics in terms of layout, building materials, geometry are presented. Moving on, the module unit with the DF systems, was modelled and simulated using EnergyPlus dynamic simulation software through the platform DesignBuilder. The HVAC system and the conditions in which the unit was examined in the platform DesignBuilder are also documented in this research. For each scenario, six different cavity depths were examined, to find out under which cavity depth each DF system is the most efficient in terms of thermal loads and primary energy consumptions. The cavity depths examined were 0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m and 1.50 m. The BIPVs and BIPV/Ts electricity production was also calculated with the use of PVSites software and through diagrams their contribution is documented. All the results are presented with the use of numerical tables and diagrams. The module was examined under Nicosia’s, Cyprus, climatic

conditions, aiming to represent the South-Eastern Mediterranean region as well, to add into the existing knowledge of BPIVs and BIPV/Ts under these climatic conditions.

The aim of the research is to investigate the passive and active contribution of a DF with integrated active solar systems, on a typical studio apartment. The intermediate semi-open space's viability in terms of thermal and visual comfort for the users, is proposed to be examined in more detailed in future research. The ultimate aim is to propose a design strategy and analysis that leads to the creation of nearly zero energy building modules, which can then be transformed into sustainable building blocks and complexes, and whether this cavity space can be used as an extension of the living space.

2 ΠΕΡΙΛΗΨΗ

Η βελτίωση της Ενεργειακής Απόδοσης των κτιρίων, παράλληλα και με τη χρήση εναλλακτικών πηγών ενέργειας είναι απαραίτητη στις μέρες μας, καθώς ο κτιριακός τομέας στην Ευρώπη αντιπροσωπεύει ένα μεγάλο ποσοστό εκπομπών αερίων του θερμοκηπίου (CO_2) και το 40% των αναγκών Πρωτογενούς Ενέργειας. Δεδομένου ότι η ανάπτυξη πολυώροφων οικιστικών συγκροτημάτων συνεχίζεται, ο σχεδιασμός παθητικών στρατηγικών και η ενσωμάτωση ενεργειακών ηλιακών συστημάτων αναδεικνύεται ως μια λύση για εξοικονόμηση ενέργειας. Επίσης, αναγνωρίζεται και ως πρακτική πράσινης ανάπτυξης κτιρίων, η οποία συνδέεται άμεσα με τη μείωση των περιβαλλοντικών επιπτώσεων. Τα τελευταία χρόνια, οι σχεδιαστές αναζήτησαν νέους τρόπους βελτιστοποίησης της Ενεργειακής Απόδοσης των κτιρίων ειδικά των πολυώροφων κτιρίων και ένας από αυτούς ήταν η βελτίωσης του εξωτερικού κτιριακού κελύφους, με την εισαγωγή Συστημάτων Διπλοκέλυφων Κατασκευών. Μέσω της εφαρμογής συστημάτων Διπλοκέλυφων Κατασκευών, οι Αρχιτέκτονες και οι Μηχανικοί κατάφεραν να εφαρμόσουν συστήματα όπου μπορεί να επιτευχθεί ο φυσικός αερισμός, να μεγιστοποιηθεί και να ελεγχθεί η ποσότητα φυσικού φωτός που εισέρχεται στους εσωτερικούς χώρους, να παρέχεται σκίαση και να προστατεύεται το κτίριο από άνεμο, υγρασία, υπερθέρμανση και ψύχος. Εκτός από τα τυπικά συστήματα Διπλοκέλυφων Κατασκευών, υπάρχει επίσης αυξανόμενο ενδιαφέρον για τα Φωτοβολταϊκά πλαίσια και πιο συγκεκριμένα για την ενσωμάτωση των Φωτοβολταϊκών πλαισίων στο κτιριακό κέλυφος (Building Integrated Photovoltaic Panels (BIPV) και Building Integrated Photovoltaic Panels/Thermal (BIPV/T) - η διαφορά μεταξύ των δύο είναι ότι με τη χρήση των BIPV/T, η θερμότητα που εκπέμπεται από τα Φ/Β πλαίσια συλλέγεται και μετατρέπεται σε θερμική ενέργεια).

Η παρούσα μελέτη ερευνά τη συμβολή τριών προτεινόμενων συστημάτων Διπλοκέλυφης Κατασεκυής, ενός συστήματος Συμβατικής Διπλοκέλυφης Κατασκευής (DF), ενός συστήματος BIPV Διπλοκέλυφης Κατασκευής και ενός συστήματος BIPV/T Διπλοκέλυφης Κατασκευής, εφαρμοσμένα σε μια μονάδα ενός υπνοδωματίου, με στόχο την ανάλυση της παραγωγής ενέργειας από τα συστήματα BIPV και BIPV/T, τα θερμικά φορτία, τις καταναλώσεις πρωτογενούς ενέργειας για θέρμανση και ψύξη. Το διάκενο μεταξύ του εξωτερικού και εσωτερικού κελύφους της Διπλοκέλυφης Κατασκευής αντιμετωπίζεται ως «βεράντα», δηλαδή ως ένας ημιυπαίθριος χώρος που λειτουργεί ως προέκταση του εσωτερικού χώρου. Αρχικά, παρουσιάζονται τα χαρακτηριστικά του στούντιο ως προς την εσωτερική διάταξη, τα δομικά υλικά και τη γεωμετρία. Προχωρώντας, η μονάδα σε συνδυασμό με τα συστήματα των Διπλοκέλυφων Κατασκευών μοντελοποιήθηκε και προσομοιώθηκε, χρησιμοποιώντας το λογισμικό δυναμικής

προσομοίωσης EnergyPlus μέσω της πλατφόρμας DesignBuilder. Το σύστημα ψύξης, θέρμανσης και οι συνθήκες υπό τις οποίες εξετάστηκε η μονάδα στην πλατφόρμα DesignBuilder, τεκμηριώνονται και παρουσιάζονται μέσα στην μελέτη. Για κάθε σενάριο, εξετάστηκαν έξι διαφορετικά πλάτη διάκενου, έτσι ώστε να διαπιστωθεί σε ποιο διάκενο το κάθε σύστημα Διπλοκέλυφης Κατασκευής είναι το πιο αποδοτικό όσον αφορά τα θερμικά φορτία και την κατανάλωση Πρωτογενούς Ενέργειας. Τα πλάτη διάκενου που εξετάστηκαν είναι 0,25 m, 0,50 m, 0,75 m, 1,00 m, 1,25 m και 1,50 m. Η παραγωγή ηλεκτρικής ενέργειας από τα συστήματα BIPV και BIPV/T υπολογίστηκε με τη χρήση λογισμικού PVSites και η συμβολή τους παρουσιάζεται μέσα από πίνακες καταναλώσεων. Όλα τα αποτελέσματα παρουσιάζονται με τη χρήση πινάκων και διαγραμμάτων. Η μονάδα εξετάστηκε χρησιμοποιώντας τις κλιματικές συνθήκες της Λευκωσίας, Κύπρος, με στόχο να αντιπροσωπεύσει και την περιοχή της Ευρύτερης Νότιο-Ανατολικής Μεσογείου.

Στόχος είναι η συγκεκριμένη μελέτη να προσθέσει στην υπάρχουσα γνώση την ανάλυση της συμβολής σε ενεργειακό επίπεδο των ενεργητικών ηλιακών συστημάτων BPIV και BIPV/T σε οικιστική μονάδα στούντιο, υπό αυτές τις κλιματικές συνθήκες. Επίσης σε μεταγενέστερο στάδιο τα επίπεδα θερμικής άνεσης και οπτικής άνεσης του διάκενου, προτείνονται να εξεταστούν πιο λεπτομερέστερα. Ο απώτερος στόχος είναι να προταθεί μια στρατηγική σχεδιασμού που θα στηρίζει τον σχεδιασμό οικιστικών μονάδων Σχεδόν Μηδενικής Κατανάλωσης Ενέργειας, οι οποίες στη συνέχεια μπορούν να μετατραπούν σε βιώσιμα οικιστικά κτίρια και συγκροτήματα και κατά πόσο το διάκενο μπορεί να χρησιμοποιηθεί και έως ημιυπαίθριος χώρος.

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4 INTRODUCTION

Through this chapter, the importance of the use of Renewable Energy Sources will be raised especially in the European Union Building Sector. From 2021, a new target was set for the European Union, stating that all new buildings must be Nearly Zero Energy Buildings (nZEBs), and Member States are encouraged to establish national strategies based on the local criteria and introduce the numerical indicator of primary energy use, in kWh/m^2y, to achieve this nZEBs target as mentioned by D'Agostino et. al [27].

4.1 Energy Demands and Greenhouse Emissions

The construction sector has a huge impact on the climatic crisis, greenhouse emissions (CO_2), since almost 40% of the global primary energy consumptions comes from the buildings [28]. Various conferences and treaties have occurred stating the importance of taking actions against Climatic Change. Starting in the '70s, the National Environmental Policy Act (NEPA) [29], managed to establish a national policy law to protect and eliminated any harm against the environment. Apart from that, it aimed to improve the health and living conditions of the people. The treaties focus on pollution control, air quality, water quality including the Environmental Impact Assessment (EIA) [30], which focuses on the strategies and policies to be followed by Countries. Due to Global Warming, the United Nations Framework Convention on Climate Change (UNFCCC) [31], established the Kyoto Protocol [32] in 1997, which had as a main target to reduce the Greenhouse Emissions (GHG) produced due to anthropogenic factors. Following the Kyoto Protocol, UNFCCC established the Copenhagen Accord in 2009, which further enhanced globally the importance of the agreement in limiting and reducing Greenhouse Gas Emissions (GHG). Moreover, the Copenhagen Accord promoted the stabilization of GHG to prevent any extreme climate changes and keep any temperature rises below 2 ^oC [33]–[35]. The latest Agreement by UNFCCC is the Paris Agreement [36] signed in 2016, which stressed the importance of limiting global warming below 2 ^oC and limiting it to 1.5 ^oC compared to pre-industrial levels. Furthermore, it aimed to support the Countries to handle any impacts due to climate change [37].

Apart from the Global Warming agreements, the European Union established a legislative framework the Energy Performance of Buildings Directive 2010/31/EU (EPBD) [38], and the Energy Efficiency Directive 2012/27/EU, which aim to encourage Energy performance in buildings by minimizing the energy needs for heating, cooling, and lighting. Thus, it aims for a better quality of life and to decrease CO_2 emissions.

This is of high importance, since the residential sector, as stated by Luis M.Lopez-Ochoa et al. [39], is responsible for 25.4% of overall energy consumption and 20.8% of CO_2 emissions in the European Union. The demand for energy in cities will continue to rise since a high percentage of people living in rural areas, are migrating to urban areas. It is projected that by 2050, 68% of the world population will move to cities [40]. The EPBD Climate Policy Framework for 2030 [41], states that by 2030 gas emissions shall be reduced by 40% compared to 1990 and by 80-95% by 2050. The targets set by the EPBD [42], are aiming towards nearly Zero Energy Buildings (*nZEB*) which means designing buildings with energy performance depending on each Country's climate conditions, primary energy factors, construction traditions and calculation methodologies. Specifically it defines an nZEB as a very high energy performance, nearly zero or very low amount of energy required, a very significant contribution of renewable energy and a numerical indicator of primary energy in kWh/m^{2}y.

This study will focus on the weather conditions of Nicosia, Cyprus, thus the building construction elements and its performance, shall comply with the nZEB standards of Cyprus, Regulatory Administrative Act 122/2020 [43]. The local legislation states that the primary energy consumption of the building for non-residential buildings shall be under 125 kWh/m^{2}y whereas for residential buildings it must be under 100 kWh/m^{2}y. For the outer building shell and roof construction, the U-Value must not exceed 0.4 W/m^{2}K. Any openings in the building (window, frame and glass) must not exceed 2.25 W/m^{2}K. Lastly, there must be at least 25% of the primary energy consumption needed, produced by renewable energy resources.

To achieve nZEB, techniques which lower the energy loads such as overheating are preferable. A study made by Gratia et al. [44], analysed the contribution of a glazed double façade, in terms of the façade's orientation and wind speed. This helped to, minimize the heat gains in an office building with floor to ceiling window openings and internal heat gains from such sources as artificial lighting. The study showed that to preserve comfort and reduce the cooling loads, it is important to apply natural cooling strategies, in this case natural night ventilation strategies, with the use of a glazed double façade. As stated by Agathokleous et al. [45], replacing building elements with BIPVs, augments the prospects of renewable energy system. This leads to the conclusion that by integrating these systems, meeting nZEB standards becomes a real possibility.

The aim of this study is to investigate the contribution to the energy needs for heating and cooling of three proposed double façade systems, which are the following. A conventional double façade (DF) system, a BIPV DF system and a BIPV/T DF system, in a one-bedroom studio housing module. The cavity depth is investigated for each scenario, as descripted in the Methodology section. Apart from satisfying energy needs, the proposed cavity space is to be used also as a veranda space, since due to its positioning it can act as an extension of the interior living space. Several apartment blocks in Cyprus, have undergone this ‘transition’ that a veranda space has been enclosed by glazing or even gypsum boards, by their dwellers. This is not allowed under the building permit regulations, though it is a common practise found in many cities, and it is documented in both old and new apartment blocks as shown in Figure 1. Thus, this research has a target to check if by legally incorporating a double façade, the resulting cavity space can contribute by improving the inhabitants’ everyday lifestyle, and by minimizing the energy performance of the module and the whole building.

Figure 1. Examples of Closing up the Veranda Space on Existing Apartment blocks in Cyprus.

As discussed, the importance of acting against the Climatic Changes and the Energy Efficiency in the building sector is stressed out through the Paris Agreement and the Energy Efficiency Directive 2012/27/EU (EPBD) in addition to all the conferences and treaties signed prior since the ‘70s. Through the three proposed façade systems, it is expected that the energy needs of the module in terms of heating and cooling will be minimised. It is expected that the two DF systems BIPV and the BIPV/T will also contribute to energy production, thus increasing the contribution from Renewable Energy Recourses. On a later stage this study aims to strengthen the knowledge on which extend the cavity depth of a Double Façade System can contribute to energy savings under Mediterranean Climatic conditions and similar areas. Also, as mentioned above, the study aims to empower the contribution of the DF cavity spaces as a new tool to design outdoor-indoor living spaces for modern nZEB apartment block buildings. As a further research apart from Energy Efficiency, the study promotes the investigation of the contribution that DF systems make on the Thermal Comfort of inhabitants following the PMV and PPD index, since the cavity space is examined as a living space as well [46].

4.2 Applications of Double Façade Systems

4.2.1 Double Façade Systems.

Even though the idea of a double façade system is not new, in the last few years there is an increasing interest from architects and engineers to incorporate double skin façade systems on buildings in terms of energy savings, applying natural cooling techniques, protecting the interior spaces from external noise pollution, wind loads and acting as an insulation against extreme temperatures. The building envelope can have a huge impact on achieving the optimal interior conditions for the inhabitants such as their thermal comfort and visual comfort. In definition, the double skin façade refers to a system which consists of two layers/skins. Usually, the layers are glass, where in the space in-between - the cavity - there is an air flow. The airflow within the cavity, can be either naturally as shown in Figure 2 (right), or fan supporting air circulation or mechanically driven circulation [5]. The air flow ventilation is necessary to avoid any overheating or condensation occurring in the cavity. The use of mechanical ventilation using an air-handling unit (AHU), can vary depending on the season. During the summer period the air passing through the cavity into the AHU system is then released in the atmosphere, whereas during the winter period the air is pre-heated in the cavity, then heated in the AHU and then released in the interior spaces as shown in Figure 2 (left).

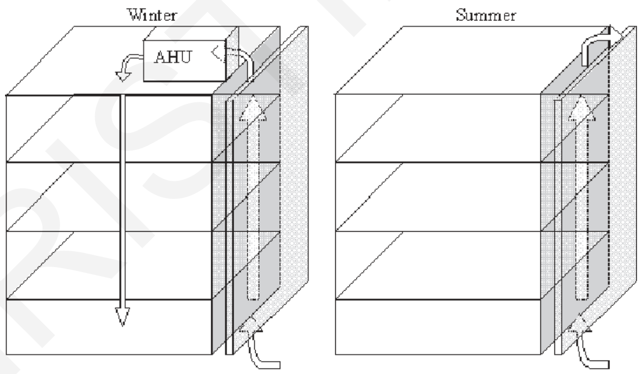


Figure 2. Diagrams of Mechanical Ventilation during the Winter Period with the use of AHU (left) and Natural Ventilation through the Cavity during the Summer Period (right) [1].

The double facades can be found in the form of a buffer façade system, an extract-air façade, a twin-face façade, and a hybrid façade. The buffer system façade was constructed to maximize the amount of daylight entering the interior spaces while increasing the sound and insulation properties of the construction. The cavity depth of a buffer zone varies between 0.25 m-0.90 m, sealed single glazing and allowing fresh air in the building with HVAC system for each floor or box type windows throughout the whole façade as shown in Figure 3 (left).

The extract air system façade consists of the main double-glazed façade and a single glazing positioned on the interior of the main façade. As shown in Figure 3 (centre), the air space between the two layers is part of the HVAC system, where the warm air within the cavity space is extracted and used by the HVAC system as fresh air for the interior. The space between the two glazing layers ranges between 0.15 m-0.90 m and this façade system is preferred in cases where natural ventilation is not possible.

As stated by Boake et al. [2], the twin-face façade is a conventional curtain wall system or a thermal mass wall system placed inside a single glazed building skin, where the external glazing can be a safety, laminated or insulating glass. Moreover, a twin-façade system, as shown in Figure 3 (right), includes openings to allow natural ventilation. The cavity space must be at least 0.50 m-0.60 m to allow cleaning and the internal skin of the system offers insulation to minimize heat loss.

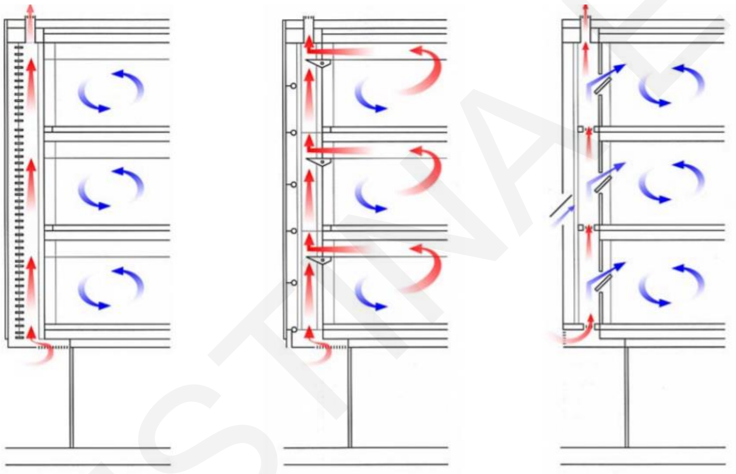


Figure 3. Diagrams: Buffer DF System (let), Extract-Air DF System (centre), Twin-Face DF System (right) [2].

Lastly, a hybrid system is a combination of one or more of the basic characteristics described in the previous façade systems to create a new system. An example of a hybrid façade is the Tjibaou Cultural Centre in New Caledonia designed by Renzo Piano Building Workshop. As shown in Figure 4, natural ventilation occurs depending on the wind forces. Due to its unique shape, the façade natural ventilation can occur through Venturi effect when there is no fresh breeze, Passive Cooling due to its conical shape and operable roof skylights and lastly when there is light to moderate wind ventilation occurs due to Stack effect [47].

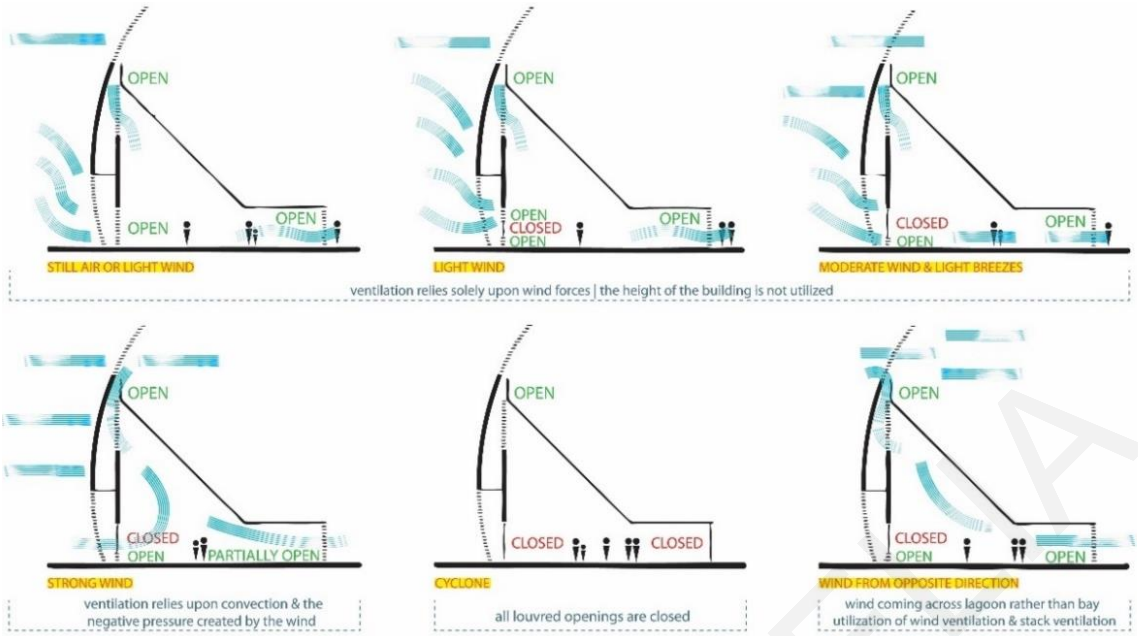


Figure 4. Ventilation Diagrams due to Wind forces, Tjibaou Cultural Centre, RPBW Architects [3].

Moreover, in buffer façade system, extract-air and twin-face façade shading devices can be introduced within the cavity, such movable louvers, or blinds. A double façade glazing system with blinds in the cavity was designed by Renzo Piano Building Workshop, for the new Courthouse building in Paris, as shown in Figure 5 through a technical section (left) and façade (right).

Figure 5. New Courthouse in Paris by Renzo Piano Building Workshop Façade Cross Section (left) [4] and Façade External View (right) [5].

In general, DF systems can be applied on buildings under cold weather conditions or warm weather conditions. Depending on the weather conditions, with some alterations such as opening or closing the inlet and outlet fins, allowing air circulation throughout the entire cavity, the behaviour of the façade system is changing. As shown in Figure 6 (right), the DF behaviour during the winter period, cold weather conditions, is portrayed showing that the cavity acts as a barrier to heat loss, meaning that the warm air within the cavity can heat up the interior spaces through heat transfer, thus reducing the energy demands for heating. On the other hand, Figure 6 (left, centre), is showing the DF's behaviour during summertime, warm weather conditions. During this period as shown on Figure 6 (left, centre), the cavity through inlets and outlets can be vented from the outside to decrease the cooling loads of the building. The excess heat is released to the environment from the top of the DF outlet, due to the chimney effect, where air density differences and the rise of air temperature in the cavity are forcing the warm air to rise, and to be replaced by a colder breeze. Warm air can also escape through the DF cavity, using internal outlets. Moreover, the cold breeze can enter the interior spaces from the DF cavity through internal inlets. Outlets and inlets can be found on each floor as well.

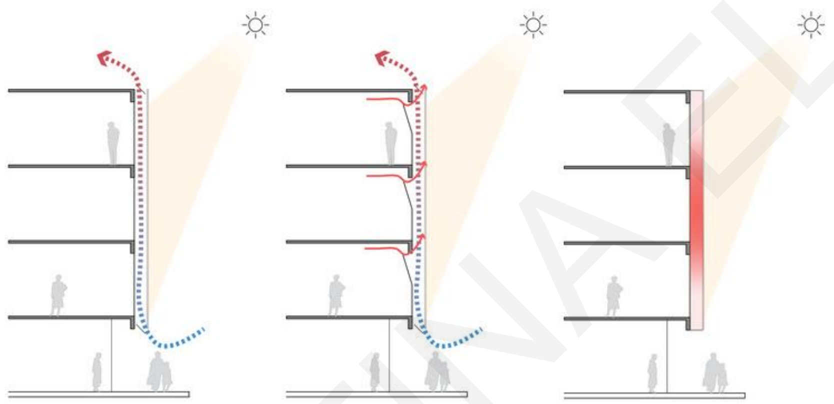


Figure 6. Double Façade behaviour alterations under warm weather conditions (left, centre) and under cold weather conditions (right) [5].

Apart from the different types of the double facade systems, the cavity space is a parameter which has an impact on the system behaviour. The cavity space can be found in the form of a box window, shaft-box, corridor type or multi-storey façade type. A box window type consists of a frame with inward openings on the external skin for fresh outside air. The cavity is divided horizontally and vertically usually on a space-by-space basis and each window requires air intake and extract openings. A shaft-box type has a box window form based on the twin face design. The system is made from box windows with continuous vertical shafts thought the entire façade to initiate stack effect. The corridor type façade refers to the cavity space which is closed for each floor level. The divisions occur along the horizontal length of the corridor where acoustic, fire protection and ventilation are needed. The air intake is found at the bottom and the extract at the top. Lastly, the multi-storey façade refers to the cavity space which runs throughout the entire façade with no divisions horizontally nor vertically and the air intake is at the bottom of the facade and the extract at the top. Figure 7 illustrates how the four different cavity alterations perform in cross section and plan view.

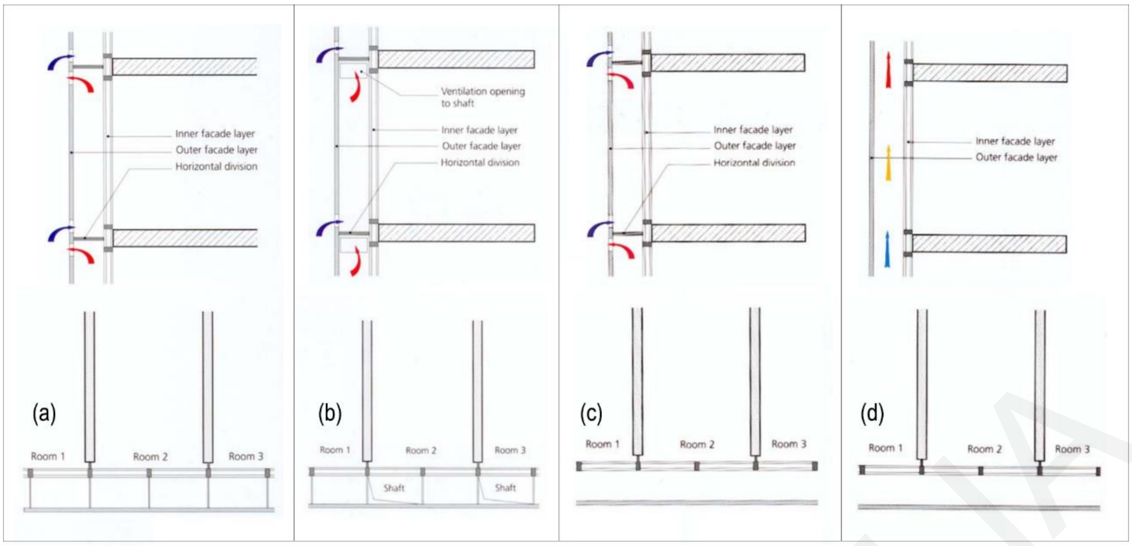


Figure 7. Cavity Space Alterations: Box Window (a), Shaft-Box (b), Corridor (c) and Multi-Storey (d) [6].

Benefits of a Double Façade System:

1. Reduces the heating and cooling loads to achieve thermal comfort.
2. Maximizes the use of natural light in the interior spaces, thus decreasing need for artificial lighting.
3. Allows clear views for visual comfort.
4. Offers acoustic, wind and thermal insulation.
5. Allows natural ventilation, improving internal living and working conditions.

Disadvantages of a Double Façade System:

1. Initial construction cost is higher.
2. High maintenance.
3. Space Consumption: The cavity space cannot be used by the inhabitants.
4. Possible failure to function properly due to external conditions, such as shading caused by surrounding buildings.

4.3 Application of BIPV and BIPVT Systems

An active solar system can either be a building integrated system (BIPV) or a building applied system (BAPV). As mentioned by Vassiliades et al. [48], a BIPV differs from the BAPV because in the first case, the active system replaces conventional building envelope materials whereas in the second case, the active systems are placed on the building envelope without any construction materials being replaced. Another difference is that BIPVs are considered as construction elements and part of the architectural design.

4.3.1 BIPV Façade Systems.

BIPV refers to the Building Integrated Photovoltaics, which means that photovoltaic panels are used in construction industry to replace conventional building materials on a building envelope. BIPVs can be placed on a façade, roofs, and skylights. Using BIPVs, the initial construction cost on conventional materials is reduced as well as the labour cost since BIPVs are prefabricated and ready to be placed. As mentioned by Cheng et al. [49], integrating PVs on a building, also lowers the costs of land and structures to maintain the panels, losses in electricity transmission and distribution are reduced since the electricity production of the BIPV are near to the point of use. Moreover, apart from lowering the initial building cost, BIPVs produce electricity which in a long term lowers the needs for conventional energy, increasing the contribution of renewable energy sources and lowering the greenhouse emissions. BIPVs can also be part of the architectural design, moving a step away from the typical rack mounted solar panels. A BIPV can offer a building moisture protection, insulation against heating and cooling, shading provision and optimization of internal comfort conditions.

Since the European Union has imposed higher standards to be reached by the member states by 2030 and 2050 for lowering the CO_2 emissions and designing nZEB buildings, BIPV technology can help realize this on high-rise buildings. A multi-storey building needs more energy to function, and, in most cases, there is not enough roof top surface area for PV panels to be applied to cover up the building's energy needs. Thus, by using the façade and the building envelope in general, this helps in covering up more surface area with RES.

As said by Agathokleous et al. [7], when PV are integrated on a second surface, heat is generated behind the PVs which is released to the environment, or it can be used to heat up the interior spaces. When the latter occurs, the system is called BIPV/T (Building Integrated Photovoltaic/Thermal) which will be discussed on the next section. As shown in Figure 8, when a PV is integrated on the outer shell of the building, an air gap is created between the two layers, external and internal skin of the building. If there is no natural ventilation or any mechanical ventilation to remove this warm air, the PV temperature increases, and this leads to lowering the PV's efficiency. The BIPV's efficiency also depends on the local climatic conditions.

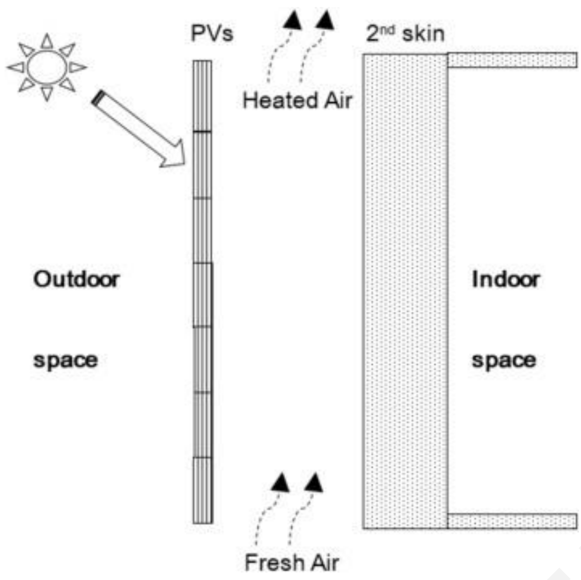


Figure 8. Schematic Diagram of a Natural Ventilated BIPV Façade System [7].

A BIPV system can be found in the form of an opaque, semi-transparent, and transparent panel. By having a semi-transparent or a transparent panel, it can provide some shading and increase the amount of natural lighting entering the internal spaces. However, increasing the PV's transparency, lowers the PV's efficiency since less solar radiation is being absorbed by the panel. BIPVs can be multifunctional building components integrated on curtain walls, greenhouses, skylights, windows, and façade cladding. Apart from the transparency aspect, other parameters that can be customized and have an impact on the panel's efficiency, are its materiality, cell colouring, cell and module size and the distance between the cells in a module. The cell efficiency depends on the absorption rate, efficiency of converting light to electric charge and efficiency to collect the charge generated. The cell can be made from crystalline silicon, monocrystalline or polycrystalline and as thin film such as amorphous silicon. Even though thin film technologies have emerged achieving high efficiency percentages, in this research, an opaque monocrystalline silicon BIPV panel will be used in configuring a BIPV Double Façade system. Monocrystalline silicon technology is preferred since it has the highest module efficiency percentage ranging from 15-20% compared to polycrystalline silicon 13-16% [50].

4.3.2 BIPV/T Façade Systems.

As mentioned above, when a PV is integrated on a building, heat is generated at the back side of the PV panel and when the heated air is mechanically driven into the building and used by the HVAC system to heat the interior spaces, this system is called Building Integrated Photovoltaic Thermal (BIPV/T). BIPV/T is a hybrid system where it can simultaneously convert radiant solar energy into electricity approximately 6-18% and the rest as useful thermal energy. Due to this, a BIPV/T system can achieve a higher efficiency compared to a BIPV system, because extracting this extra heat between the two skin layers. In this way the PV/T's temperature is not rising and overheating in the air gap is avoided. In Figure 9, the main features of a PV/T collector are shown.

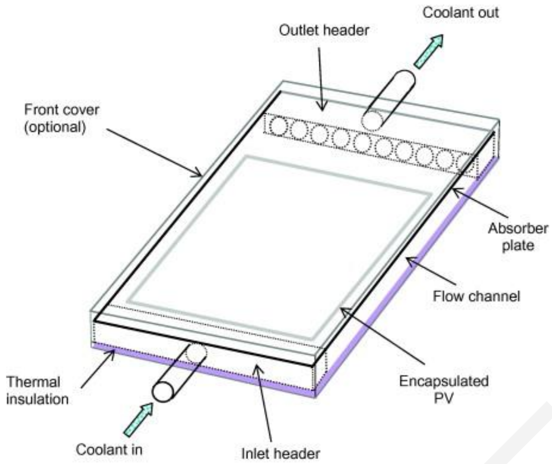


Figure 9. Diagram Showing the Main Features of a PV/T Collector [8].

In Figure 10, a schematic diagram of the BIPV/T is shown, illustrating that the excess heat from the PV panel with the use of a mechanical fan is used to heat up the interior space. As mentioned by Athienitis et al. [51], in a BIPV/T system a cooling fluid which can be water or air, is extracting heat from the PV through an open-loop or a close-loop configuration. The outside fresh air passes under the PV panel integrated envelope resulting to cooling the PV modules and recovers the useful heat which in other conditions it would be lost by released to the environment. This can be an added advantage of a BIPV/T compared to a BIPV system, because when cooled, there is more electricity being produced and there is also energy conversion to useful heat. Apart from heating up the internal spaces, this thermal energy can be used to heat up domestic hot water (DHW), as the BIPV, the BIPV/T's efficiency also depends on the local climatic conditions.

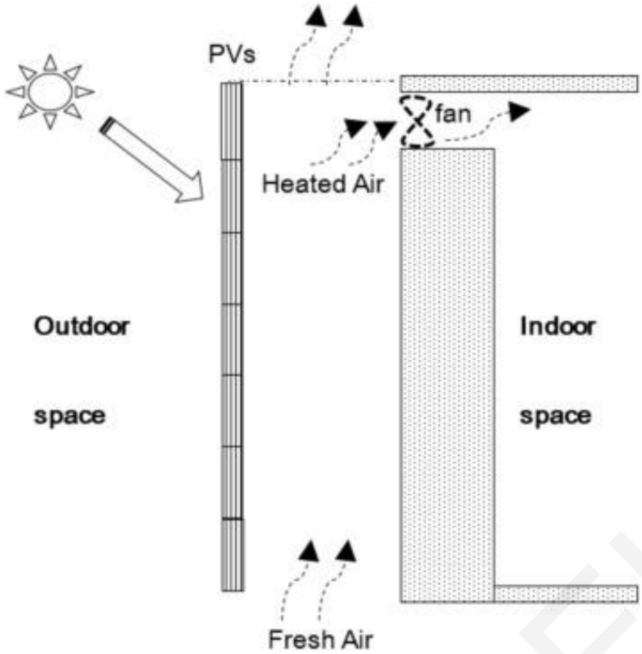


Figure 10. Schematic Diagram of a BIPV/T Façade System Extracting or Retracting Hot Air from the Building with the use of a Fan [7].

As with a BIPV system, the application of a BIVP/T system can offer thermal insulation to the building, waterproofing the building envelope, improve the internal room temperature to achieve thermal comfort, increase the use of RES on high rise buildings, move towards green building architecture, nZEB buildings, and lower the initial material building costs. As mentioned by Chow [8], some of the parameters in the BIPV/T's efficiency, operating mode and working temperature depend on the type of solar cells, flat-plate or concentrator type, glazed or unglazed panels, natural or forced fluid flow, and by being a stand-alone panel or building integrated features. For this research, a building integrated photovoltaic panel will be used, with monocrystalline silicon solar cells.

4.3.3 PV's Performance Depending on Temperature.

As mentioned above, temperature is an important parameter for the performance of a PV system, this being either a BIPV or a BIPV/T. As mentioned by Kalogirou [52], the performance of the solar cell depends on the cell temperature, where this temperature can be determined by an energy balance, by stating that the absorbed solar energy which is not converted to electricity, is converted to heat. This excess heat is then released to the environment. As shown in Figure 11, PV Power decreases when temperature rises, thus in applications where heat removal is not possible, such as the BIPVs, this heat must be mechanically removed to keep the panel's efficiency at its maximum.

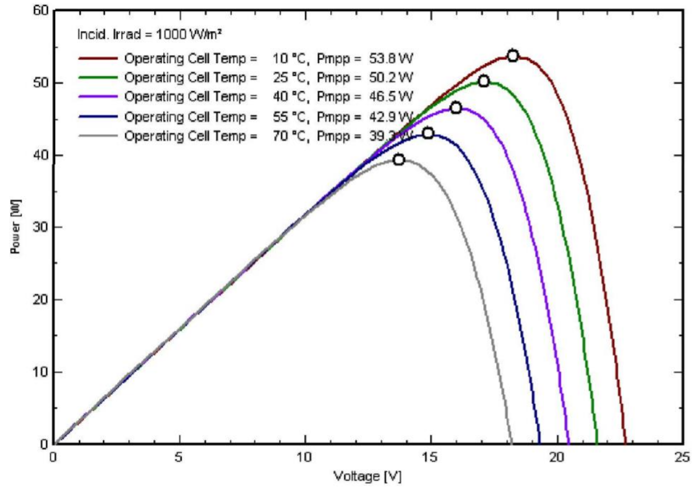


Figure 11. Graph Showing the Output PV Power and Voltage Characteristics Depending on Different Temperatures [9].

Solar cells are semi-conductors, which means that when they are exposed to light, a DC current is generated. As semi-conductors, solar cells are sensitive to temperature. As temperature rises, voltage decreases leading to less electricity production. The temperature coefficient compared to the voltage is characterised by the following equation:

$$\frac{dV_{oc}}{dT} = \beta = -0.33\%/^{o}C$$

where:
dV_{oc} = difference in Voltage Open Circuit
dT = difference in Temperature

As mentioned in this research paper, a twin-face façade is used in combination with an alteration of a multi-storey facade type cavity space. To allow for natural ventilation air flow throughout the cavity space, a perforated floor for the cavity space is introduced horizontally, to maintain the stack effect. At the same time this helps to create the veranda spaces for the inhabitants. Also, in this research the cavity space is vertically divided for each module, to maintain the inhabitants' privacy. No shading is applied in the double façade for neither of the scenarios. The contribution of the BIPV and the BIPV/T DF system will be examined in terms of the thermal loads and primary energy needs. Also, this research is aiming to investigate if this cavity space can be part of the living space, so that it will not be an unused space or to be enclosed by the inhabitants destroying the building's architectural aesthetics.

5 LITERATURE REVIEW

Through this chapter, there will be an analysis of previous research projects done in terms of the contribution in energy consumption of a conventional double façade system, BIPV façade system and a BIPV/T façade system. Also, the techniques used by previous researchers will be discussed. Moreover, emphasis will be given to some existing examples of buildings as case studies to observe the extend of the contribution that the techniques used have had on the overall energy consumption.

5.1 Research on Similar Applications

The research examines the contribution in energy consumption that a conventional double façade system, BIPV façade system and a BIPV/T façade system may have on a studio apartment module. To examine this, one must understand the importance of energy efficient buildings. As stated by Arif et al. [53], there is the need for new resources of energy, leading to nZEB, since the conventional energy sources are reaching their limits. Moreover, their study on the energy contribution of a hybrid nZEB system which comprises a PV power system with maximum electricity production 234,739 kWh, proved to be 9.5% more economically profitable than a grid only system with payback time 1.84 years. Apart from the implementation or integration of active solar energy systems, the contribution of the natural light is also a very important factor achieving nZEBs. Facing the window openings towards the sun direction, South oriented for the purpose of this study, maximises the amount of daylight reaching the interior spaces. As mentioned by Carletti et al. [54], improving the integration of daylight in buildings may contribute to the energy savings for artificial lighting, since lighting uses approximately 19% of the global electric energy consumption.

As stated by Ahmed et al. [55], the double skin façade envelope consists of an external, mostly glazing and an internal layer. The space in between is a buffer zone that may be used for ventilation and solar control. The outer layer can provide protection against any weather conditions and act as an acoustic barrier to the interior spaces. The internal layer, usually glazing as well, may be constructed with or without any operable windows. In the inner space, also referred as the cavity space, shading devices such as blinds are in most times incorporated to avoid any unwanted direct solar rays/gains entering the interior spaces. Excess solar gains can increase the need for cooling during the summer period and any unwanted sunrays may reduce the visual comfort of the users. As mentioned by Chan et al. [56], an airtight double skin façade can increase the thermal insulation of the building leading to decreasing the energy needs for heating during the winter period. Whereas by moving the air within the cavity space of a ventilated DSF it can absorb the heat energy gains of the external glazing, thus reducing the heat gains and the cooling energy needs of the building. Lastly the air cavity between the external and the internal layers can vary from 20 cm up to 2 m. As mentioned by Pomponi et al. [57], the cavity depth and height, orientation, the cavity ventilation system, if it is natural or mechanical, and if there are shading devices in the cavity, are the parameters that paly a huge role on the energy savings in terms of cooling, heating, lighting, and ventilation, which can range from 30% - 90%. This also implies that there is a reduction on CO_2 and GHG emissions.

As mentioned by Alrashidi et al. [58], the integration of PV panels (BIPV) and more specific constant or static semi-transparent PV panels, is very encouraging since the can provide control over solar heat gains and control the amount of daylight entering the interior spaces and also generate electricity. Li et al. [59], come to agree with that by proving that the energy produced by integrating semi-transparent photovoltaics on a building, has reduced the electric energy needed for lighting and cooling annually by 1,203 MWh. Also, in an environmental point of view, there has been a reduction of 852 tons of CO_2. Taking it a step ahead, Peng et al. [60], investigated the energy savings potential of a ventilated photovoltaic double-skin façade (PV-DSF) where it is argued that this system, compared to a non-ventilated PV-DSF system, it can save about 35% of electricity use per year. In terms of controlling daylight, it allows a considerable amount of daylight to enter the interior with a maximum monthly average daylighting illuminance about 300 LUX, which resulted in saving almost 50% of lighting electricity during the winter period.

Apart from the application of a DF and a semi-transparent BIPV-DF system, this study also investigated the contribution of a building integrated photovoltaic/thermal system BIPV/T. A BIPV/T hybrid system can simultaneously convert radiant solar energy into electricity and thermal energy. It is a combination of a typical photovoltaic panel as the external layer and a solar thermal collector installed on its back which preheats the domestic hot water. Compared to a standard BIPV, a BIPV/T collector has less energy losses since it uses the solar energy for both electrical and thermal energy. Due to this, it allows for the PV panel not to overheat thus decreasing its efficiency as the temperature rises. Kim et al. [61], come to agree with this statement since they compared the efficiency of a BIPV/T facade system and of a non-ventilated BIPV façade system, showing that a BIPV/T system prevents any efficiency decrease. On the contrary, it helps the PV panel to be more energy efficient. Piratheepan et al. [62] investigated the performance of a BIPV/T in terms of optical and thermal parameters and suggest that this facade system can complement any roof mounted PV system into achieving nZEB. A study made by Ibrahim et al. [63], showed that a PV/T system can achieve an energy efficiency between 55% and 62%. Barone et al. [64], through simulations investigated the electrical performance of a BIPV/T system compared to a BIPV system, proving that their proposed low-cost air-based PV/T collector prototype offers primary energy savings of 11.0-19.7 MWh/year, 52%-80% respectively, and there is a reduction of CO_2 emissions by 4.64-10.4 t_{co2}/year. Panao et al. [65], studied the energy results of the BIPV/T façade system that was integrated on the SOLAR XXI building in Lisbon Portugal. SOLAR XXI is a highly efficient building since the final energy consumption comes to be $1/10^{th}$ of the energy needs compared to a new building. The energy produced and the energy needed are very close, which means SOLAR XXI meets the criteria of a nZEB.

The contribution of a DF system on the energy performance of a building, is presented in the literature. Additionally, several researchers have proven that when BIPVs or BIPV/Ts are integrated on a DF, the energy savings are even higher. The research presented here will focus on the contribution of three proposed double façade systems on heating and cooling loads of a building unit, which will then be investigated, discussed, and compared through graphical representations. The novelty of this study is that the contribution of the cavity depth in terms of energy savings, will be tested in combination with the integration of photovoltaic panels on the double façade system proposed. Also, the study suggests that the veranda space cavity depth, can be also used as a living space for the studio apartment.

5.2 Case Studies

Before proceeding into designing the three proposed façade systems, the layout of the one-bedroom studio apartment and its semi-open space, existing implemented techniques have been examined. These, in combination with the case studies discussed previously, come to contribute to the final layout and façade systems used for the quantitative research of this paper's investigation which will follow.

5.2.1 Semi-Open Space, Balcony: Transformation of 530 dwellings / Lacaton & Vassal + Frederic Druot + Christophe Hutin

Lacaton & Vassal architects in a collaboration with architects Frederic Druto and Christophe Hutin, won a competition in 2016 for the complete renovation of a social housing structure built in 1960s and one of their main additions was the extension of the balcony with a small garden as shown in Figure 12. The architects' vision was to provide the inhabitants with 'winter gardens' which means that the balconies become part of the living spaces, thus enjoying more usable space, more natural lighting and more views, visual comfort. What is more, the balconies give the opportunity to the users to have a private outdoor space as if the user was in a private house. Large, glassed sliding doors open and close depending on the user's comfort. The addition of the new façade of corrugated aluminium and the glazed balconies, reduced the energy consumption by 50%. Usually, balconies are unused and most of the times people use it as a storage place, however the architects' approach in this project, gives the balconies a new meaning, by being a useful liveable extra space the user [66], [67].

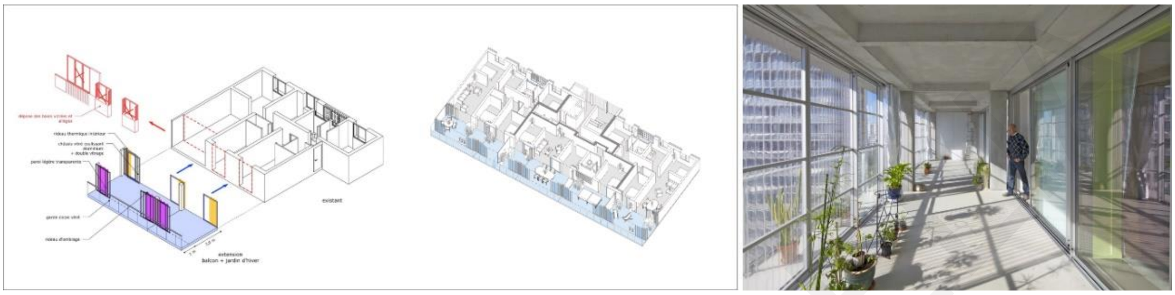


Figure 12. Diagram of Semi-Open Space Transformation of 530 dwellings and View of the Balcony [10].

5.2.2 Semi-Transparent BIPV Façade Systems: House of Music in Aalborg, Denmark

Semi- Semi-transparent photovoltaic cells not only contribute to the energy production, but at the same time they can offer heat and sun protection, sun shading and allowing a significant amount of natural light to enter the interior spaces. Moreover, semi-transparent PV façade system can be more aesthetically desirable since it gives the perception of a more transparent, light building. What is more, by having semi-transparent PV modules, it can improve the visual comfort of the users. A building that has incorporated such a system is the House of Music in Aalborg by Coop Himmelb(l)au architects as shown in Figure 13.

For the design of the South facing façade of the House of Music, the architects collaborated with an expert façade builder team to integrate the finest form of sustainable electricity generation into the building. The study aimed for a façade system which would ensure the optimum shading of the interior spaces whereas allowing the optimum amount of daylight entering the building. The outcome was a triangular shaped 2.3 m x 2.3 m module covered with semi-transparent perforated cells, in combination with perforated sheet metal panels. The modules also act as windbreakers and due to their position, the building's window can be open without any distraction. Last but not least, the façade system can produce 70 kWh/m^2 year of electricity [11], [68].

Figure 13. South Façade(left), BIPV Façade System(middle-right) [11].

5.2.3 *Solar Fabrik building in Freiburg, Germany*

The headquarters of Solar Fabrik Company in Freiburg Germany is a building which its energy needs are completely covered by the integrated PV modules on its façade and roof as shown in Figure 14, in combination with a Heat/Power generating unit which runs off with plant oil. In 1999 it became the first CO^2 neutral factory in Europe. Its South-facing façade is mainly consisting of glazing which allows the sun to enter the building and it reduces the energy needs for heating and lighting.

There are 275 m^2 of PV modules integrated on the South-facing façade and 300 m^2 mounted on the roof of the building. The PV modules integrated on the South-facing façade not only produce energy for lighting and heating, but because of their strategic position and angle of integration, they block the sun by entering the building during the summer months where the sun is high. On the contrary they allow the sun to enter the building during the winter months, since the sun is lower, thus reducing the energy needed for heating. The integration of PV modules on the façade, also helped in saving money on the construction cost, since the number of the construction materials got reduced [69], [70].

Figure 14. South Facing Façade (left, right) Interior Space (middle) [12].

5.2.4 *California Academy of Sciences / Renzo Piano*

The California Academy of Sciences building is in San Francisco, California USA, and the main architects is the office Renzo Piano Building Workshop. The design layout and the choice of materials take advantage of the natural resources such as maximizing the natural lighting by covering up to 90% of the occupied spaces, natural ventilation, rainwater recovery and energy production. The building has been awarded with LEED platinum certification. The transparent canopy covering the entire perimeter of the building is covered with Photovoltaic cells as shown in Figure 15, which cover 5%-10% of building's electricity needs. The glass canopy embodies 60 000 photovoltaic cells which provide shade for the visitors, they are part of the design and act as an attraction interest to the visitors. These photovoltaic cells approximately generate up to 213 kWh/year of electricity [14], [47].

Figure 15. Semi-Transparent PV Canopy Side View, Top View, View from Below
(starting from left to right) [13], [14].

5.2.5 SOLAR XXI Office Building / Pedro Cabrita + Isabel Diniz

Solar XXI building is in Lisbon, and it is the work of Pedro Cabrita and Isabel Diniz. The building is set to be as an example of a low energy building which uses passive systems for heating and cooling towards a nZEB. Its main and unique feature is its South façade as shown in Figure 16 (left) which consists of PV system with heat recovery which helps in energy savings for heating during the winter season. Its orientation is facing towards South so that the PV panels collect the maximum direct solar gains and there is natural light coming through the working spaces.

The BIPV/T system covers up 96 m^2 of the building façade and there are also PV panels covering up 16 m^2 of the roof and 205 m^2 of the parking area. As mentioned by Goncalves et al. [71], the total amount of electric energy needed for the building was 36 MWh and the overall amount of electricity produced from all the PV systems, was around 38 MWh. Also, Panao et al. [65], proved that the energy consumption of SOLAR XXI comes to be 1/10th of the energy needs of a standard new building. As shown in Figure 15 (middle) during summertime the BIPV/T façade provide shading for the interior spaces, lowering the needs for cooling, whereas during wintertime as shown in Figure 16 (right) there is enough natural light entering the spaces through the glass façade openings, lowering the needs for heating.

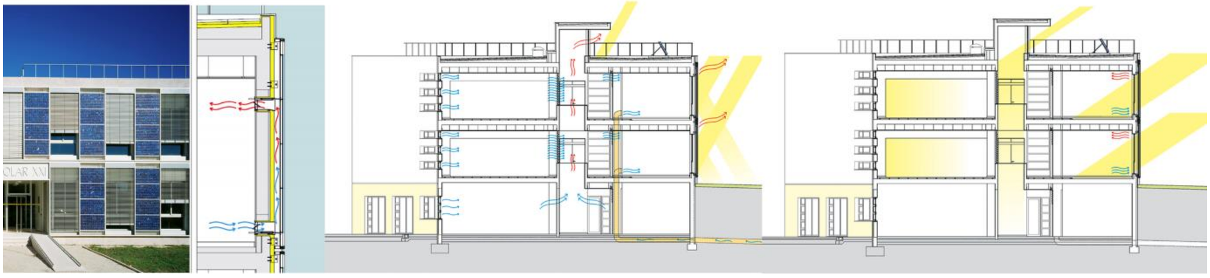


Figure 16. South Façade with BIPV/T, Diagram of the Heating Effect during Winter season, Cross Section Summer Strategy, Cross Section Winter Strategy (starting from left) [15].

Based on the above through the literature review articles and the existing built projects, it can be observed that the implementation of a double façade with integrating BIPVs and BIPV/Ts, it can lower the energy needs, lower the initial construction costs, and aesthetically add to the architectural design. Incorporating Renewable Energy Sources on a building, it can help in realising the European Union's target into moving towards nZEB buildings. Moreover, lowering the Greenhouse Gas emissions due to the building industry, will help tackling the climate change phenomenon.

6 CORRIDOR DESIGN LAYOUT AND HOUSING UNITS

Through this chapter, the module design idea in relation to the corridor, 'streets', maximising the access to natural lighting, introducing the garden idea within the living space and natural ventilation will be examined. Le Corbusier was a pioneer in these ideas, starting with sketches such as Freehold Maisonettes and Plan Obus and moving on into build projects such as the Unites d'Habitation. These projects along with the Barbican complex, will be discussed through this chapter.

6.1 Modular Design Linear and Stacked Blocks

6.1.1 Le Corbusier - Freehold Maisonettes and Plan Obus.

In 1922, Le Corbusier's sketch of Freehold Maisonettes illustrated the idea of a mass production building block consisting of clear pathways as corridors, identical apartment units been stacked and multiplied following a grid column and slab structure, in combination with communal spaces. In fact, as mentioned by Davies in 'The Prefabricated Home' [72], Le Corbusier was influenced by the traditional building types of monasteries where the monks had their own cell with a small, fenced garden and all those individual cells were part of a bigger complex with communal spaces. This balance between the private and the communal spaces, is expressed in all his projects.

As said, in 1922 his first attempt following this principle was the drawing of Freehold Maisonettes. The design portraits an eight-storey apartment block with communal sports and entertainment spaces on the roof. What was original and unique about the design at the time, was that each unit was like a duplex taking up two storeys with double height living rooms with a balcony which was not a typical balcony space but a considerable garden. Figure 17 (right), illustrates the idea that the garden for each unit, is completely shut off from its neighbour. Overall, the units are considered as individual homes with a garden which are stacked up to form a multi-storey apartment block as shown in Figure 17 (left).

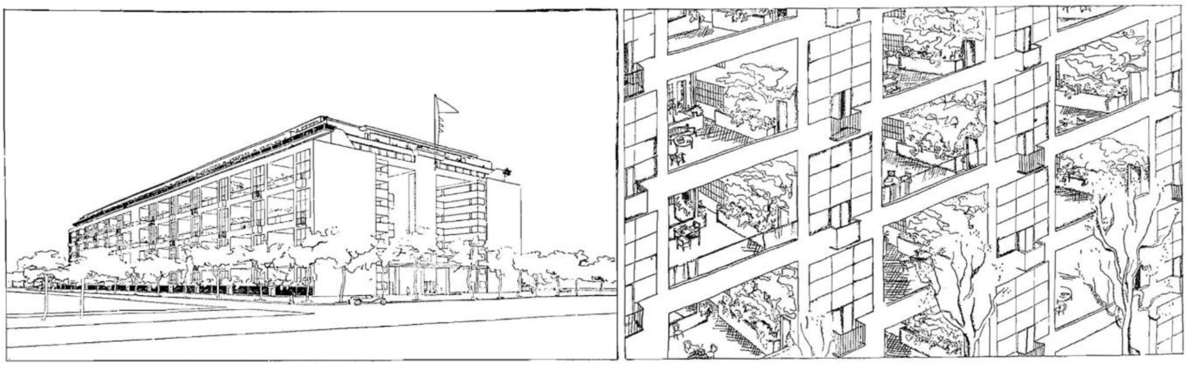


Figure 17. ‘Freehold Maisonettes’, General View of the Entire Block (left), Close up Showing Each Garden is Completely cut off from its Neighbour (right) [16].

In Figure 18, the organisation of the maisonettes is shown in plan-view, where the shading indicates the hanging gardens. Also, in plan-view, the organisation of the garden as a private, enclosed space from the neighbours can be observed. The design consists of 100-120 maisonette modules per floor in several storeys, and each one module designed to have a double height living space and its own garden. The entrance was designed at the street level with staircases leading up to each storey, and then a common main corridor, leads the inhabitants to their individual housing units. As mentioned previously, communal sports and entertainment facilities were placed on the roof top of the entire complex, however, each maisonette was designed to facilitate its own sports room. Apart from the organisation of spaces, on each balcony and the roof top, the idea of greenery, trees, and flowers, was introduce thus the hanging gardens.

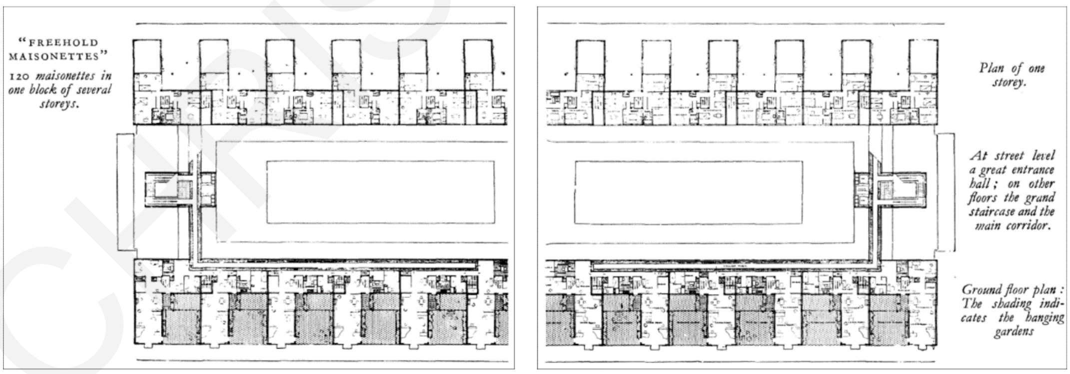


Figure 18. ‘Freehold Maisonettes’, Arrangement of Maisonettes in Plan-View [16].

Freehold Maisonettes among other visionary urban projects by Le Corbusier such as the Ville Contemporaine and the Plan Voisin, focused on the idea of housing villas as mass housing forms, and since then, as mentioned by Davies [72], the theoretical solution of the dilemma of an individual house versus mass low-cost housing projects among designers, builders and politicians had encapsulated. The

Freehold Maisonettes promoted the idea of social housing with communal services and individual maisonettes with emphasis on sufficient and practical spaces.

Moving on from the stacked module, in 1933 after his visit to Algiers, Le Corbusier proposed Plan Obus, where his sketch was illustrating a highway along the roof of the building block, where the building block would be consisted of a double-loaded corridor with deep plan and single-aspect apartments on both sides. Even though following this configuration all the units would have access to a balcony, due to its single side design, there would be limited daylighting and limited cross ventilation. However, what can be argued in this configuration, is the number of variations in the facade treatments of the individual dwellings. Plan Obus can be described as a megastructure which gives the opportunity to the inhabitant, to have the same amount of architectural freedom as if he/she would live in a detached house along a street. Figure 19 illustrates the idea of people living side-side with the freedom of different dwelling facades.

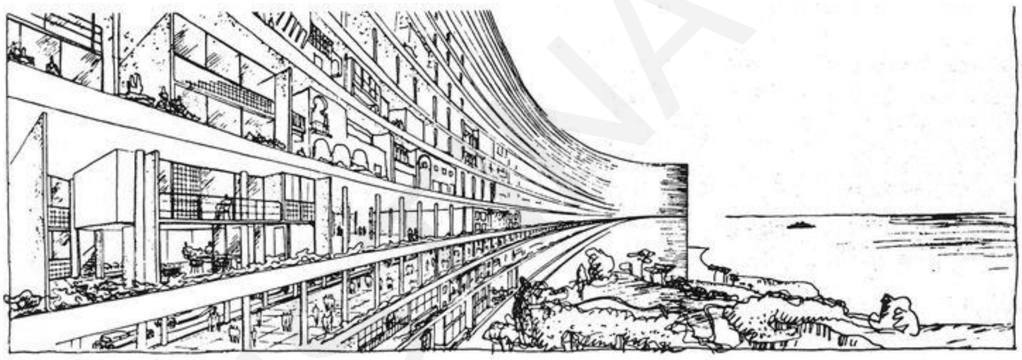


Figure 19. Plan Obus, Living side by side [17].

Even though Plan Obus was never constructed, Le Corbusier developed this idea into a later project, the Unités d'Habitation, which will be discussed in the next section. Apart from his own work, Le Corbusier was able to inspire other Architects to follow the idea of a habitable megastructure. Some of the examples through the years of habitable megastructures after Plan Obus, can be seen in the Brazilian Architect Affonso Eduardo Reidy's work in 1969 'Pedregulho Neighbourhood Redevelopment' in Rio de Janeiro. Moving on in 1994, through the work of Dutch Architect John Habraken, 'Next 21 Building' in Osaka which had as an objective among other to create a variety of residential units with substantial natural greenery throughout the entire building. In more recent years in 2010, a modern interpretation of this habitable megastructure, can be seen in the work of the Swiss Architects Herzog de Meuron 'Beirut Terraces', where this time the façade seems to follow a random appearance of diversifying each storey. In Figure 20, the work of Affonso Eduardo Reidy's 'Pedregulho Neighbourhood Redevelopment' (left), John Habraken's 'Next 21 Building' (centre) and Herzog de Meuron 'Beirut Terraces' (right) are shown.

Figure 20. Habitable Megastructures: Affonso Eduardo Reidy's 'Pedregulho Neighbourhood Redevelopment' (left) [18], John Habraken's 'Next 21 Building' (centre), Herzog de Meuron's 'Beirut Terraces' (right) [17].

6.1.2 Le Corbusier - Unités d'Habitation.

As said previously, Le Corbusier's Plan Obus was never constructed, however he developed that idea through the design of the social housing called Unités d'Habitation. After the Word War II there was a need for new social housing throughout the whole Europe and in 1947, Le Corbusier was commissioned to design a multi-family residential apartment block building in Marseille, France. Unités d'Habitation is seen as an iconic representation of Brutalism, with 18-storey slab building block with an overall 337 apartments and described as a machine for living in. The architect believed that this design idea was a solution to rehousing the mass after the World War II, where inhabitants could have their own private spaces and be able to shop, eat, exercise, and gather within the same complex. In Figure 21 right, his famous drawing of lifting the units and stacking them up in a building. Within the building there are 23 typologies of the apartment units accommodating from one-bedroom apartments to larger family units. Regardless of the typology, each unit has at least one balcony.

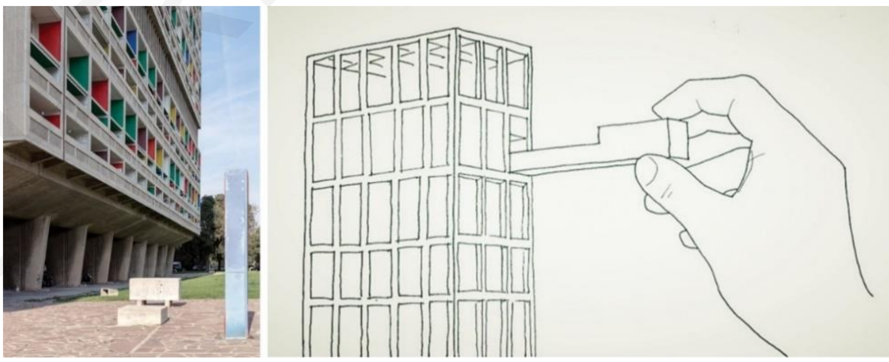


Figure 21. Unites d'Habitation Façade (left) [19], Illustration of Lifted Units (right) [17].

By rotating the entire building block at true north, the architect managed to provide all the units with windows facing East and West, where this means that throughout the whole day, there is access to natural lighting. Quoting the architect his idea was to 'provide with silence and solitude before the sun, space and greenery, a dwelling which will be the perfect receptacle for the family and to set up, in God's good nature, under the sky and the sun, a magisterial work of architecture, the product of rigour, grandeur, nobility, happiness and elegance' [20].

The block follows a strict grid and proportions to create the living units. The narrow flats, as shown in Figure 22 (right) in a cross section, are mostly designed as two storey height duplexes with a double height living room at one end. This idea is multiplied throughout the whole building, where pairs of duplexes interlock surrounding the central corridor. One of the most unique and important parameters of the design, was the organisation of spaces within the housing units. Following the idea of the duplexes interlocking and providing natural lighting daily, the balcony on both ends allows for cross ventilation as well. As seen in Figure 22 (left), the balcony is incorporated within the living space, and it can be used throughout the whole year. Again, as described in the Freehold Maisonettes, the balcony area is treated as a private room completely separated from the neighbours.

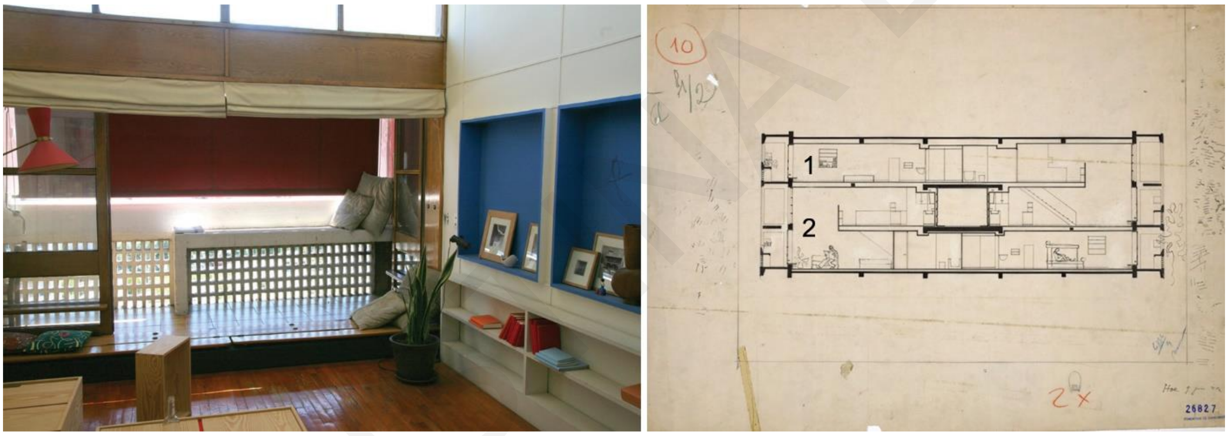


Figure 22. Unites d'Habitation Interior Veranda Space (left) [19], Cross Section (right) [20].

As shown in Figure 23, the internal corridors of Unités d'Habitation are described as a street 'rue intérieure' which means entry corridors. The streets' intention, as described by the architect, was to design clear access to the apartment blocks, along with access for all the necessities and services for the building. Corridors and access points having the character of a street, it transforms Unités d'Habitation into a vertical city, bringing the streets into the sky.

By conceptualising a city within a building, Unités d'Habitation, apart from the apartment blocks, contains two commercial streets with double height on the seventh floor and eight floor, with large openings allowing the entry of natural lighting. There is also a hotel on the seventh floor, eighth floor where it was first designed so that residences could invite guests to stay and a communal rooftop terrace. As mentioned by Monteys Roig et al. [73], the commercial street on the seventh floor, described as a gallery-street, it can be considered as a predecessor of a street with daily goods supply which further connects the building as a vertical city. Apart from been described as a commercial street, the gallery-street is seen as a socializing point which also provides protection from bad weather conditions.

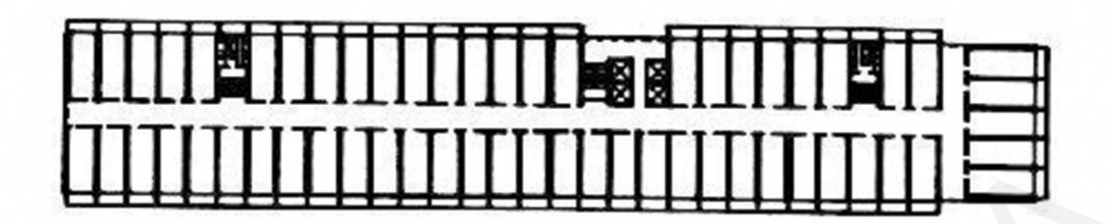


Figure 23. Unites d'Habitation Plan View [19].

Even though the corridors with the building were described as streets, there is another aspect that by looking at the situation, Figure 24 shopping street (left) versus the enclosed corridors (right) which give access to the living spaces, the corridors leading to the residential units are much darker since there is no access to natural lighting. The idea of a double height corridor, a commercial street was only applied on 2 floors, which highlights the importance of natural lighting.

Figure 24. Unites d'Habitation Shopping 'Street' (left) [20], vs Living Spaces 'Street' (right) [21].

Through Unités d'Habitation's organisation of spaces, interlocking duplexes, Le Corbusier managed to create a complex where all the residential units had access to a balcony space, green spaces, and natural lighting. The balcony area is part of the living space that can be used in summertime and during the wintertime. Even though sometimes is impossible for circulation areas to have access to natural light when designing a multi-storey residential building but looking at the two pictures of the corridor idea one can argue the importance of natural lighting. Le Corbusier's design techniques for both the residential units and the idea of a corridor to be treated as a street with big window openings, were pioneer ideas which even today they may be considered as a luxury to have in multi-storey residential buildings.

6.1.3 Chamberlin, Powell, and Bon - The Barbican.

Another post-war building living complex, the Barbican, was designed in 1950 in London by Chamberlin, Powell, and Bon Architects. The Barbican is one of the largest built examples of Brutalist architecture and it promotes a 'utopian ideal for inner-city living' which is located in the overcrowded city of London [22]. The complex was designed as to be a 'vertical garden city', an urban hub having residential blocks surrounding a communal area in the middle, inspired by the concept of Unites d'Habitation.

The Barbican Estate is characterised by its rough concrete exterior surfaces, Figure 25 right, its high-rise residential towers, and its elevated gardens. The vision of the entire complex was that schools, commercial sector, restaurants, and cultural destinations could be incorporated within this high-density residential building blocks creating a living hub. As shown in Figure 25 left, the entire complex consists of three high-rise residential blocks 43-storey high each and 17 apartment and commercial facilities on the lower-level blocks 7-storey high each.

Figure 25. The Barbican Complex Site Plan (left) [22], and Brutalist Architecture Facades (right) [23].

The architects' main objective was to design a clear separation between the private areas, the communal spaces, and the public areas and at the same time allow for undisrupted pedestrian pathways that visitors and residents can explore the complex on foot. The public areas are found on the elevated first level of the 7-storey high blocks. Elevated streets, high walks, create a network of bridges which is the access circulation walkways for the apartment units.

Almost all the blocks within the complex are raised higher than street level, on a 'pilotis' of columns, allowing for pedestrians to wonder around the site. The Barbican is characterised by wide open walkways,

Figure 26 left, elevated walkway systems, exposed staircases and overlooking balconies. As seen in Figure 16 right, both the balconies and the elevated walkways aimed to incorporate greenery in the residents' everyday life.

Figure 26. The Barbican Walkways Ground Floor Street Level (left) [23], and Lifted Streets (right) [22].

Figure 27 illustrates the typical floor plans and a typical split level apartment unit. The tower blocks and the terrace blocks' apartment layouts were designed to maximize the amount of natural lighting within the internal spaces. Again, as in the work of Le Corbusier, each apartment unit has at least one balcony space, which branches off the bedroom, the study room, and the living room. In the Barbican, the bedrooms, dining rooms and living rooms were positioned along the external walls to allow for natural lighting, whereas the kitchen and the bathrooms were positioned against the internal walls. The units design aimed for young professionals and the internal spaces have simple layouts with compact kitchens and bathrooms.

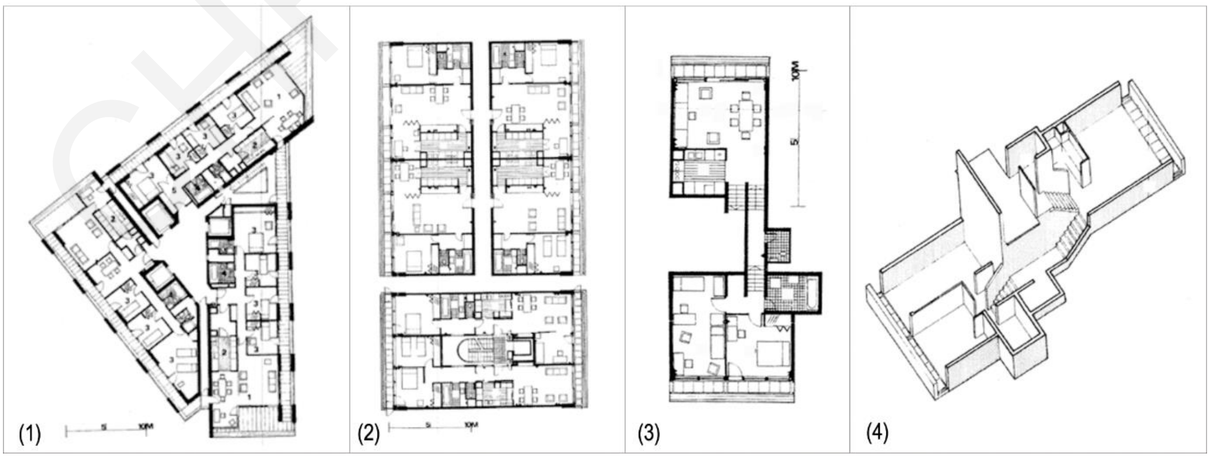


Figure 27. Typical Tower Plan (1), Typical Slab Plans (2), Typical Flat Plan (3) and Axonometric diagram of a Split-Level Apartment (4) [22].

The Barbican complex consists of 2 113 flats ranging from studio to three bedroom flats, of 41 different types where 94% are privately owned. The modules follow the same internal layout theme, where every module has access to at least one balcony. Each block is limited to one or two types of accommodation, a cohesive design and a subtle social stratification.

As the residents point out, they see Barbican as a self-contained urban village, with exclusive garden access, private inner society, and quality living within the residential units [23]. 'Every interior confirming that you are, in your own small way living as part of a grand design'.

Following these architectural precedents, the points taken from the above examples among others, include firstly the importance of natural lighting in people's everyday life, secondly the importance of a balcony space and greenery incorporated in the living space and lastly the positive impact that a wide-open bright corridor can have into a resident's everyday life and psychology. The apartment module unit presented in this research, follows the idea of a simple one-studio unit with a balcony space facing North. In a more theoretical aspect, the concept of designing this module is that by duplicating the module forming a multi-storey building block, the access to the units follows the idea of a corridor design.

7 METHODOLOGY

Throughout this chapter, the research methodology is being presented by analysing every step taken for the final conclusions. Firstly, the climatic conditions which the different scenarios have been analysed are being introduced. The climatic conditions play a significant role in this investigation, since these parameters have a great impact on the amount of energy needed for heating and cooling. Moreover, the results from this investigation can apply to regions with similar climatic conditions. Later, the three double skin façade systems are being introduced as well as the qualities of the building materials used. In each case, the configurations of the two spaces examined, are being presented. On the following chapter, the results are being documented and analysed. The results for each scenario are analysed and later the different cavity depths are evaluated among them. Lastly the evaluation of the results is documented, to understand the contribution of each system in terms of thermal loads and primary energy savings.

7.1 Methodology of Investigation

The research focuses on the thermal impact the veranda cavity space, has on the thermal loads of a one-bedroom housing unit in terms of the energy needed for heating and cooling. The simulations were done using the EnergyPlus dynamic simulation software through the platform DesignBuilder [74]. DesignBuilder software has been used by a numerus of studies which investigated the energy consumptions of a building and simulations regarding energy saving potentials, such as the study made by Huang et al. [75], energy performance of a residential building. A series of diagrams and tables are produced to document the simulation outcomes.

7.2 Climatic Analysis

The climatic conditions in which the scenarios will be tested, Nicosia Cyprus, were analysed to understand their potential and how to incorporate them with the design to reduce the energy needs for cooling, heating and artificial lighting. Apart from the advantages, the disadvantages such as excessive sun radiation, must also be taken into consideration to protect the interior spaces from overheating, thus increasing the energy needs for cooling during the summer period. The data from the Department of Meteorology of Cyprus [76], has been studied.

7.2.1 *Daylight, Sunshine Hours and Solar Energy*

The area records high levels of natural light throughout the whole year as well as high levels of sunshine as shown in Figure 28 (left) [24]. Also, as shown in Figure 28 (right) there is intense solar radiation mainly during the summer months with the maximum recording being 8.5 kWh in June while the lowest in December 2.5 kWh [25].

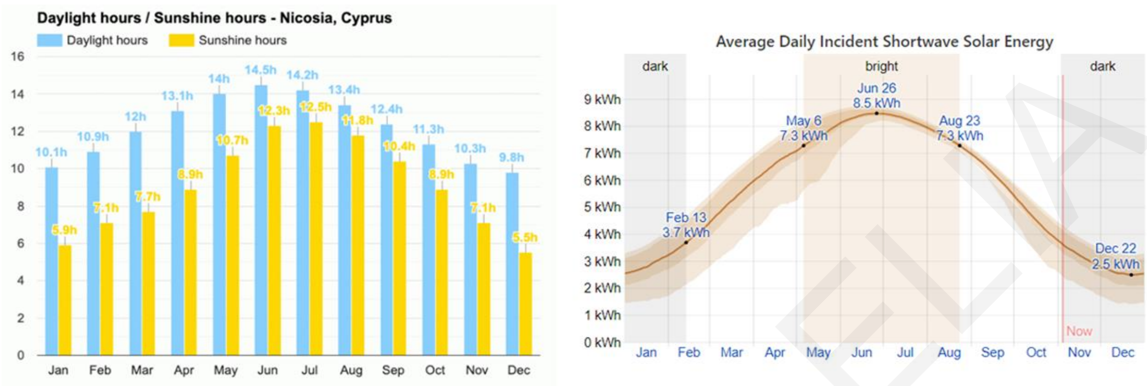


Figure 28. Daylight hours/Sunshine hours Nicosia Cyprus (left) [24], Average Daily Incident Shortwave Solar Energy (right) [25].

7.2.2 *Average High and Low Temperatures*

In the area of Nicosia, the winter period is characterized as mild, and the summer period as hot and dry. As shown in Figure 29 (right) the maximum temperature ranges from 22 °C to 33 °C and the minimum temperature from 6 °C to 15 °C. During the summer period, there are some extreme heat waves with the temperature reaching or even exceeding 40 °C. Also, as shown in Figure 29 (left), there are several temperature fluctuations during the day [25]. The highest temperature is recorded in July and the lowest in January.

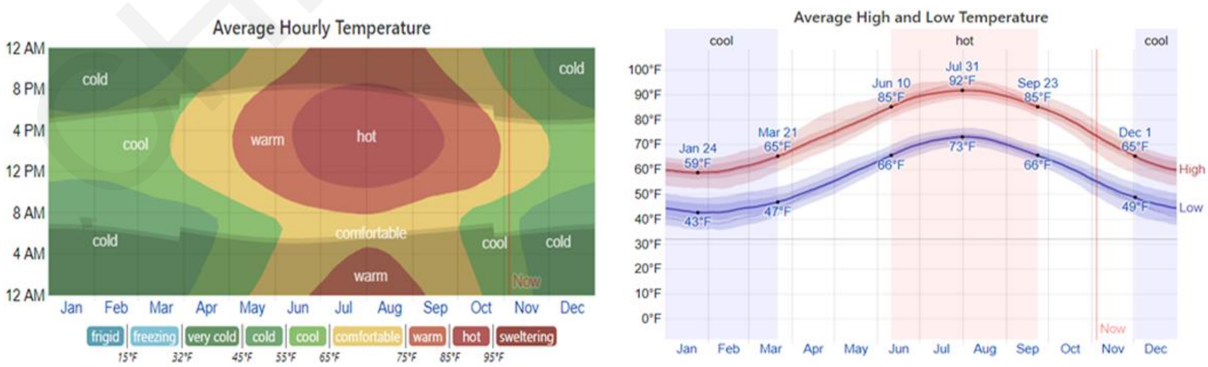


Figure 29. Average Hourly Temperature (left), Average High and Low Temperature (right) [25].

7.2.3 Wind Analysis

As shown in Figure 30 (left), there is a substantial fluctuation in wind speed during the year with the strongest winds being observed at a speed of 4,25 m/s starting from November reaching 5 m/s until February and during the period starting from April until October, the wind speed fluctuates between 3,5 m/s and 4,25 m/s. Also as shown in Figure 30 (right), it is observed that during the winter season, the wind direction is mainly Southeast while during the summer season it is mainly Westerly with Northwest [25].

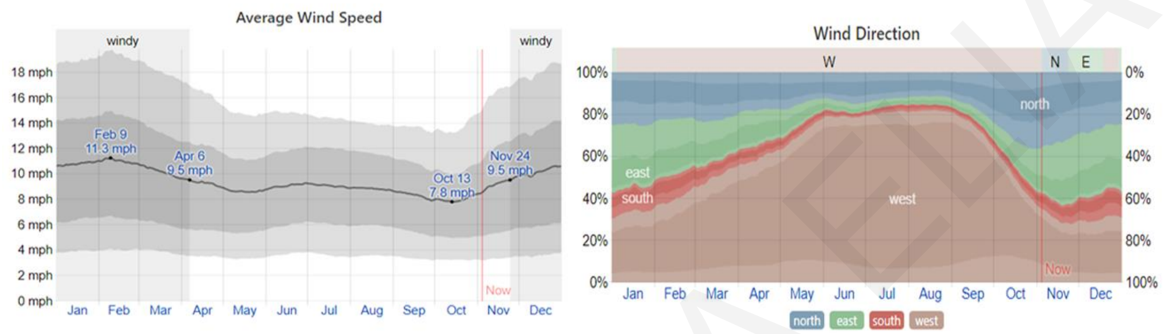


Figure 30. Average Wind Speed (left), Wind Direction (right) [25].

Observing the climatic data of the area, attention must be given to sun protection, especially during the summer months. Also, there are high levels of solar radiation throughout the year thus with the placement of photovoltaic panels doubling up as shading devices, should have a positive effect on reducing energy consumption. In addition, there are high levels of natural light, that can be incorporated in the design, to lower the energy consumption for artificial lighting.

7.3 Module Design

7.3.1 Organisation of Space.

The three DF systems were modelled using the platform DesignBuilder and the results were obtained by simulating the modelled system through the commercial software EnergyPlus. As shown in Figure 31, zone 1 is the living space of the studio apartment, thus the thermal zone examined and zone 2 is the outside veranda space referred also as the cavity space between the double façade system and the glass window doors of the studio. The purpose of this set up, is to examine the thermal impact of the veranda on the thermal loads of the internal living space. In architectural point of view, the results will examine where this space can have a positive impact on the thermal loads and be used as part of the living space for the inhabitants. Following the idea of having access to natural lighting, all the cases evaluated are facing towards the South. The cavity depth range is set to start from 0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m and 1,50 m. The depths 0.25 m, 0.50 m and 0.75 m are not considered as a veranda space nor a liveable space, just as a DF system. The living space follows an open plan simple layout with dimensions 6.50 m x 4.25 m, 3.00 m height and an area of 27.6 m^2.

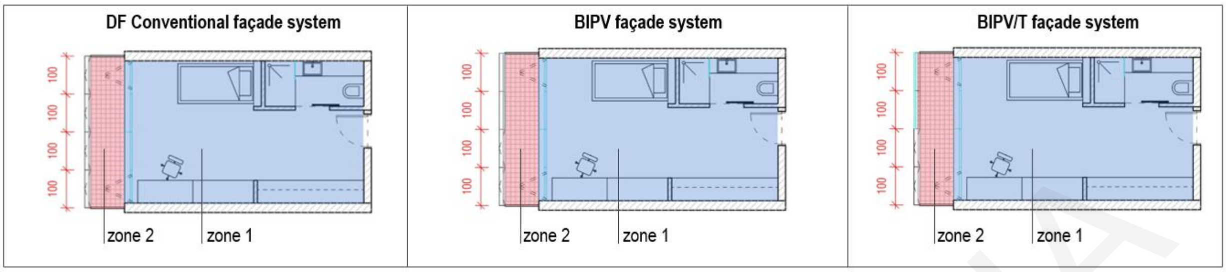


Figure 31. Organisation of thermal zones, Plan View.

Even though the study represents the energy needs of one module, the conditions that the module was examined, are set to be as in reality. This means, that the module is treated to be in-between other internal spaces as shown in Figure 32.

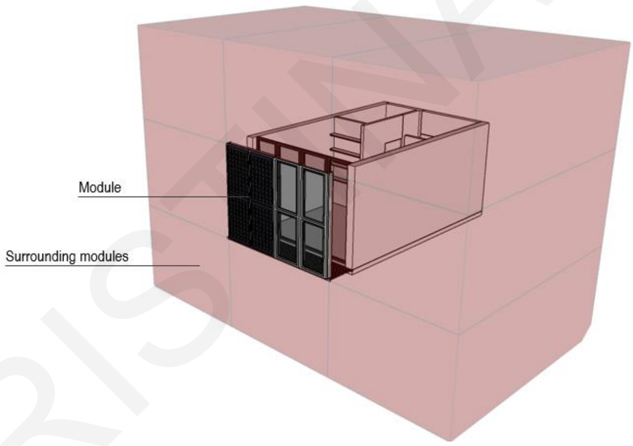


Figure 32. Module design within its context.

7.3.2 Building Construction Envelope.

The entire building envelope follows the most common construction technique used in Cyprus where the external walls consist of 25 cm of hollow thermal brick and 2.5 cm plaster both internally and externally. Thermal insulation of 8 cm thickness is placed on the external side of the wall and the overall wall thermal transmittance (u-value) is calculated to be 0.233 W/m^2K. The ceiling construction consist of 0.4 cm waterproof membrane externally, 8 cm thermal insulation, 20 cm reinforced concrete and 2.5 cm of plaster internally with an overall u-value 0.337 W/m^2K.

The module construction itself was treated as an internal space since the conditions under which it was examined were set as in reality. The internal wall construction consists of 2.5 cm plaster on both sides of the wall and in between 10 cm hollow brick was placed with an overall thermal transmittance 2.10 W/m^{2}K. The internal roof construction consists of 1.2 cm wood flooring, 14 cm screed, 15 cm reinforced concrete slab and 2.5 cm plaster with an overall thermal transmittance 1.00 W/m^{2}K.

Placing the thermal insulation on the external layer of the envelope, is done to achieve a well-insulated airtight module, limiting thermal bridges. Minimizing thermal bridges, leads to minimizing heat loses. Air leakages occur at different material construction joints; thus, a continuous insulation is preferred to avoid any heat loses from those points. This is a key factor to achieve nZEB buildings, where in combination with passive solar energy techniques the overall heat load and heating energy demand for the building can significantly be reduced as mentioned by Hallik et al. [77].

Thermal transmittance, *u-value* [W/m^{2}K], is defined as the rate of heat transfer in Watts *W*, through 1m^2 of a structure divided by the temperature difference, in Kelvin *K*, across the structure. The lower the u-value of a construction is, the better insulated the building envelope is. To calculate the thermal transmittance of a construction, the thickness *d,* measured in meters *m*, the thermal conductivity λ [W/mK] and the thermal resistance *R* [m^{2}K/W] of each material is needed. The thermal conductivity calculation for the walls and ceiling construction, was based on the method described in the standard CYS EN ISO 6946:2007 [78].

Thermal resistance *R* [m^{2}K/W] is defined as a measure of how resistant a material is to the heat transfer across it. The higher the thermal resistance value of a material, the better it acts as an insulator [79]. The thicker the material *d*, the higher its thermal resistance. Since the relation between thermal resistance *R* [m^{2}K/W] and thermal transmittance *u-value* [W/m^{2}K] is inversely proportional, the higher the R-value, the lower is the U-value.

Thermal conductivity λ [W/mK] is defined as the rate at which heat is transferred by conduction through a unit cross-section area of a material when a temperature gradient exists perpendicular to the area [80]. To achieve good construction insulation and minimize the heat exchanges, a low thermal conductivity insulating material is preferable. In this case, extruded polystyrene is used with thickness ρ >20 kg/m^3 and thermal conductivity λ 0.03 W/mK.

Table 1. Thermal Transmittance Calculation for External Walls.

External Walls				
	Material Construction	**Thickness d (m)**	**Thermal Conductivity λ (W/mK)**	**Thermal Resistance R (m^2K/W)**
1	Stucco/Plaster (internal)	0.03	1.00	0.030
2	Thermal Brick	0.25	0.18	1.389
3	Extruded Polystyrene	0.08	0.03	2.667
4	Stucco/Plaster (external)	0.03	1.00	0.030
Rsi **(m^2K/W)**				0.130
Rse **(m^2K/W)**				0.040
Thermal Transmittance **(W/m^2K)**		**0.233** (value less than the Legislation ≤ 0.400)		

Table 2. Thermal Transmittance Calculation for External Roof.

External Roof				
	Material Construction	**Thickness d (m)**	**Thermal Conductivity λ (W/mK)**	**Thermal Resistance R (m^2K/W)**
1	Waterproof Membrane	0.004	0.230	0.170
2	Screed	0.050	1.350	0.037
3	Extruded Polystyrene	0.080	0.030	2.667
4	Reinforced Concrete	0.200	2.500	0.080
5	Stucco/Plaster (internal)	0.030	1.000	0.030
Rsi **(m^2K/W)**				0.100
Rse **(m^2K/W)**				0.040
Thermal Transmittance **(W/m^2K)**		**0.337** (value less than the Legislation ≤ 0.400)		

As far as the window openings doors and windows, the equivalent tables 6.15 - 6.16 from the document *'Guide to Thermal Insulation of Buildings, 2nd edition'* [78], were used. The proposed window doors are double glazing 4-12-4, low-e value ≤ 0.15, with 90% argon and 10% air in the gap. The overall u-value used for the glass $U_g = 1.6\ W/m^2K$ and the frame $U_f = 2.0\ W/m^2K$, is 2.00 W/m^2K, with light transparency factor (*VT)* 0.70 and solar heat gains (*SHG)* 0.39.

The solar factor *SHG* is the percentage of the sum of the solar radiant heat energy entering the room through the glass. Since there are extreme weather conditions during the summer period, temperature such as 40 ^oC, it is important for the SHG value to be as small as possible. On the other hand, light transmittance *VT* is the percentage of visible light that can pass through the glass, entering the room. The higher the VT value, more light enters the room, while by lowering the VT value there is more energy need for artificial lighting. The ideal percentage value for VT for weather conditions such as Cyprus, is between 60%-80%. The construction characteristics of the building, the module, and the veranda depth are shown on table 3.

Table 3. Construction Characteristics of the Building and the Module.

Building and Internal Modules	**Thermal Conductivity [W/m²K]**		**Cavity Depth [m]**	**Thermal Conductivity [W/m²K]**	**Glazing Characteristics**	
	*External Internal Wall	*External Internal Ceiling	Zone 2 Range	Double-Glazing Window Doors	Solar Factor **(SHG)**	Light Transmittance **(VT)**
Building Block	*0.233	*0.337	0.25-1.50	2.00	0.39	0.70
Conventional DF	2.100	1.000	0.25-1.50	2.00	0.39	0.70
BIPV Facade	2.100	1.000	0.25-1.50	2.00	0.39	0.70
BIPV/T Facade	2.100	1.000	0.25-1.50	2.00	0.39	0.70

The Cyprus legislation for new buildings 122/2020 [43], indicates that the thermal transmittance for external roof, external walls, slabs, and columns must be ≤ 0.4 W/m²K. For windows and glass doors, the thermal transmittance must be ≤ 2.25 W/m²K. Furthermore, the legislation states that the Primary Energy needs for housing units, must be ≤ 100 kWh/m²y, whereas for commercial buildings it must be ≤ 125 kWh/m²y. Moreover, it states that at least 25% of the overall Primary Energy needs, must be covered by Renewable Energy Resources *RES*.

As stated above, the building envelope constructions comply with the Cyprus legislation for buildings 122/2020 [43]. For all the material characteristics and thermal transmittance calculations, the document *'Guide to Thermal Insulation of Buildings, 2nd edition'* [78], based on the Cyprus Regulations, was used.

7.3.3 Convective Heat Transfer Coefficient Assessment for the Depth Cavity.

To understand the heat transfer conditions due to convention in the DF system's cavity space, an analysis on the three convention boundary layers was done. The idea behind this analysis, was to firstly understand and then decide on the appropriate boundary layer, that the energy transfer within the cavity space will be occurring, for this research paper. On table 4, the main characteristics of the three convention boundary layers are: the velocity boundary layer, the thermal boundary layer, and the concentration boundary layer.

Table 4. Convention Boundary Layers Coefficients [26].

Convention Boundary Layers (Energy Heat transfer between a surface and a fluid moving over the surface)		
	Convection heat and mass transfer between a surface and a fluid flowing past it	
Velocity Boundary Layer	**Thermal Boundary Layer**	**Concentration Boundary Layer** *[bulk fluid motion (advection) and the random motion of fluid molecules (conduction or diffusion)].*
Coefficient **Friction** coefficient *Cf* $C_f \equiv \frac{\tau_s}{\rho u_\infty^2/2}$	**Coefficient** **Convection heat transfer** coefficient *h* $h = \frac{-k_f \partial T/\partial y\|_{y=0}}{T_s - T_\infty}$	**Coefficient** **Convection mass transfer** coefficient *hm* $h_m = \frac{-D_{AB} \partial C_A/\partial y\|_{y=0}}{C_{A,s} - C_{A,\infty}}$
Parameters *x* – velocity component of the fluid *u* *y* – increasing distance from the surface	**Parameters** t – temperature δ_t – thickness (y)	**Parameters** δ_c – thickness (y) C_A -molar concentration of the mixture
Boundary Layer Characteristics	**Boundary Layer Characteristics**	**Boundary Layer Characteristics**
When **fluid particles meet the surface**, their **velocity** is reduced significantly relative to the **fluid velocity** upstream of the plate, and for most situations it is valid to assume that the particle velocity is zero at the wall.	A thermal boundary layer must develop if the **fluid free stream and surface temperatures differ**.	Species (Fluid) transfer by convection between the surface and the free stream fluid is determined by conditions in the boundary layer; it is of interest to determine the rate at which this transfer occurs.
*For flow over any surface, there will always exist **a velocity boundary layer and hence surface friction.***	*Thermal boundary layer, and hence convection heat transfer, will always exist **if the surface and free stream temperatures differ.***	*Concentration boundary layer and convection mass transfer will exist if **the fluid's species concentration at the surface differs from its species concentration in the free stream.***
	**Local and Average Convection Coefficients – Heat Transfer* *the surface heat flux and convection heat transfer coefficient both vary along the surface.*	**Local and Average Convection Coefficients – Heat Transfer* *If a fluid of species molar concentration CA, flows over a surface at which the species concentration is maintained at some uniform value, transfer of the species by convection will occur.*
*Laminar and Turbulent Velocity Boundary Layers	*Laminar and Turbulent Thermal Boundary Layers	*Laminar and Turbulent Species Concentration Boundary Layers

For this research, the conditions in the cavity space will be based on the thermal boundary layer coefficient, setting the temperature as the main variable. This is done because the module will be examined under temperature differences which occur throughout the whole year, compared with the other two boundary layers, where velocity boundary layer has the velocity difference as its main parameter and respectively the concentration boundary layer has the difference of the boundary's fluid concentration level compared to the free stream's fluid concentration.

7.3.4 Modelling the Scenarios.

In Figure 33, the 3D representation of the three DF systems is shown. For each scenario, the cavity's ceiling and floor is a perforated metal sheet, to allow air movement in the cavity due to stack effect. Starting from left, the first scenario is a conventional double façade system with the external glazing windows with no daylight control system within the cavity such as blinds. The second scenario is the BIPV façade system (centre) where half of the façade is covered with semi-transparent PV panels covering 5.25 m^2 and the other half is a window glazing conventional DF system. The third scenario is the BIPV/T façade system (right) covering 5.25 m^2 and the rest is a window glazing conventional DF system.

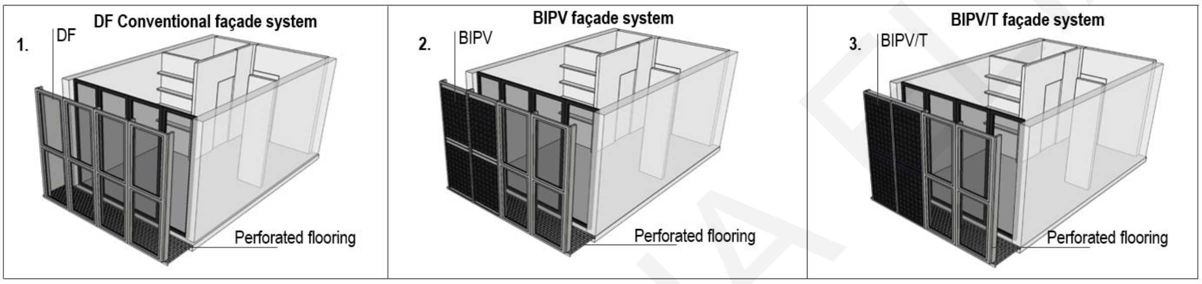


Figure 33. DF Conventional (left), DF BIPV (centre), and DF BIPV/T (right).

Figure 34 illustrates the air movement through the cavity of the double façade system. As mentioned in section 4.2.1, the cavity space follows the multi-storey idea that the air flow is occurring throughout the entire façade with air intake at the bottom of the façade and air extract at the top. In this research, the cavity space is vertically divided to ensure privacy for the inhabitants and is horizontally divided for each module with a perforated metal sheet to create the veranda flooring and still allowing the air flow.

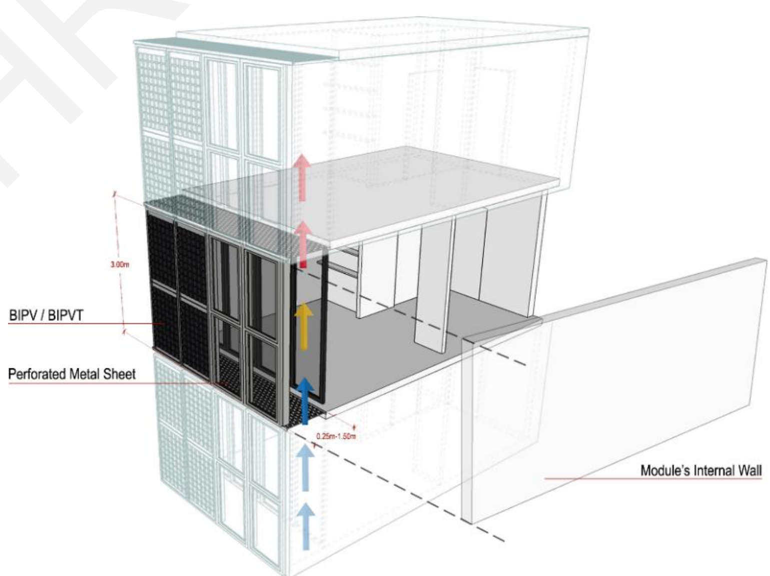


Figure 34. Diagram of the Air Flow Through the Cavity Space.

7.4 Design Builder Modelling

The scenarios were investigated using EnergyPlus dynamic simulation software through the platform DesignBuilder. As mentioned in section 7.1, the weather conditions of Nicosia, Cyprus will be used. The activity of the module was set to be a student-housing unit, with occupancy 0.03 person/m^2, 1 person in total and the office equipment power density was set to 1.50 W/m^2. For the primary energy consumptions calculations, the CoP value for heating was set at 3.0, heat pump, and for cooling at 3.5. As mentioned in section 7.3.2, the module was treated and modelled as an internal space in DesignBuilder. The u-value for the internal walls was 2.10 W/m^{2}K, the internal ceiling 1.00 W/m^{2}K and for the veranda's double-glazing doors 2.00 W/m^{2}K was used.

Figure 35 represents the scenarios as modelled using the DesignBuilder platform. Starting from left is the Conventional Double façade system, BIPV façade system and last the BIPV/T façade system model. All the simulations results were later compared among all the calibrated models for each case separately. As a first step, the module was designed and calibrated without having any veranda space. This was done so that the initial energy needs of the module would be recorded and used as the base model to compare the different cavity configurations.

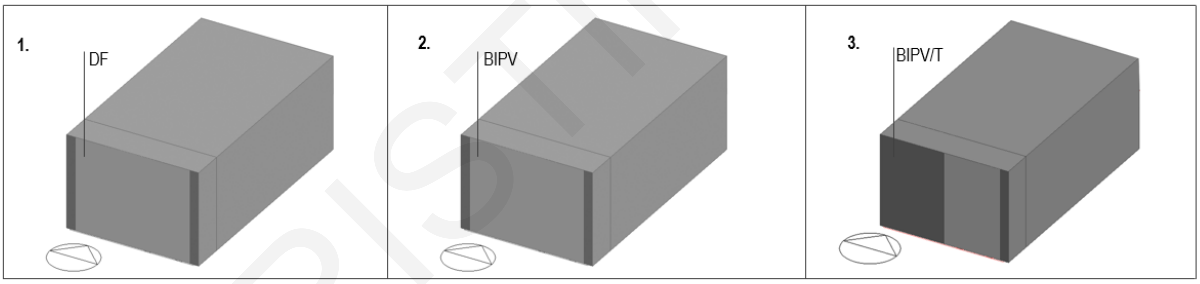


Figure 35. 3D Modules as modelled in DesignBuilder Platform.

As mentioned in methodology section 7.3.1, Figure 32, the module is not treated as an individual unit, ,it is however evaluated as being part of a building block. The environmental conditions entered in DesignBuilder Software to obtain this are shown on table 5.

Table 5. Environmental Control Values set in DeisgnBuilder.

Heating Setpoint Temperatures (°C)	**Cooling Setpoint Temperatures (°C)**	**Humidity Control (%)**
Heating: **20.0**	Cooling: **26.0**	RH Humidification setpoint: **40.0**
Heating Set Back: **10.0**	Cooling Set Back: **28.0**	RH Dehumidification setpoint: **60.0**

Figure 36 represents the final form of the entire block drawn into DesignBuilder. The centre module was modelled as a thermal zone as shown above, with the veranda space as it will be explained in the following paragraph. In terms of the surrounding module units, component blocks were used. They have the same dimensions in width, length, and height as the main module. Also, there is no HVAC system, no artificial lighting or any occupancy used for the component blocks. The component blocks are not included in the thermal calculations, since the analysis focuses on the thermal characteristics and energy consumptions of the centre module.

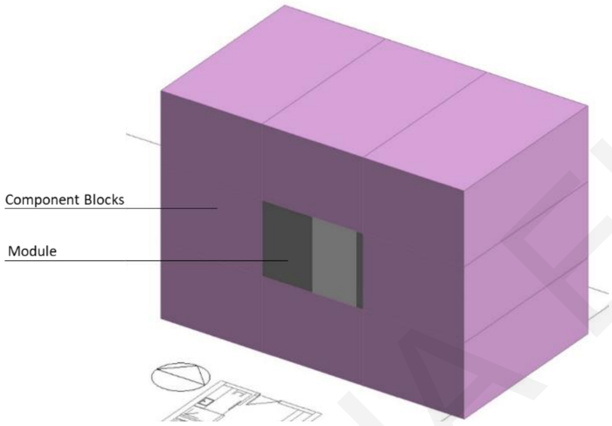


Figure 36. Final 3D Model Configuration as Drawn in DesignBuilder Software.

Tables 6-8 represent how the cavity depth varied for the three DF system evaluations. For all the cases the different cavity lengths tested are 0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m and 1.50 m. No HVAC system or artificial lighting were selected for the veranda space and occupancy was set to 1 person, 0.03 people/m^2. To represent the perforated ceiling and floor of the veranda space, a hole covering half of the ceiling and floor's area respectively was created. Lastly, the veranda zone was included in the thermal calculations.

Table 6. Conventional Double Façade Cavity Length Variations.

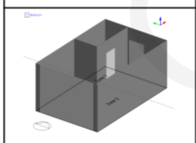
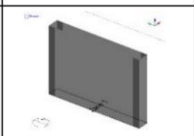
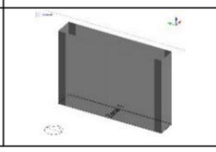
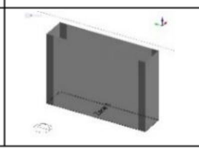
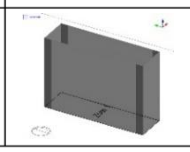
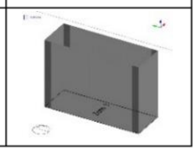
1. DF Conventional						
DesignBuilder Model No Balcony	DesignBuilder Model Cavity Space 0.25m	DesignBuilder Model Cavity Space 0.50m	DesignBuilder Model Cavity Space 0.75m	DesignBuilder Model Cavity Space 1.00m	DesignBuilder Model Cavity Space 1.25m	DesignBuilder Model Cavity Space 1.50m
						

Table 7. BIPV Double Façade Cavity Length Variations.

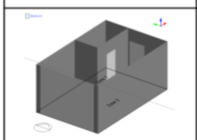
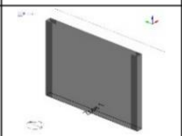
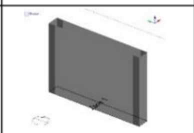
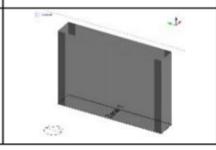
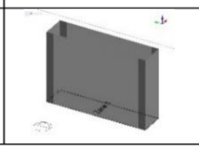
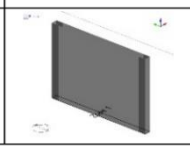
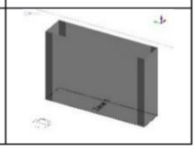
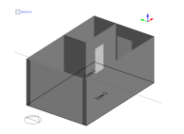
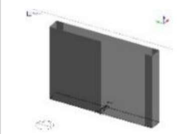
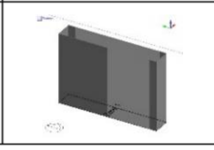
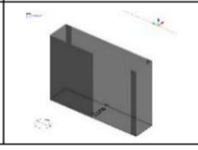
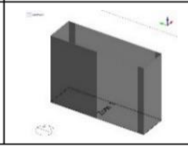
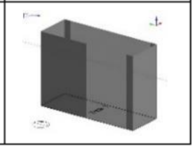
2. DF BIPV						
DesignBuilder Model No Balcony	DesignBuilder Model Cavity Space 0.25m	DesignBuilder Model Cavity Space 0.50m	DesignBuilder Model Cavity Space 0.75m	DesignBuilder Model Cavity Space 1.00m	DesignBuilder Model Cavity Space 1.25m	DesignBuilder Model Cavity Space 1.50m
						

Table 8. BIPV/T Double Façade Cavity Length Variations.

3. DF BIPV/T						
DesignBuilder Model No Balcony	DesignBuilder Model Cavity Space 0.25m	DesignBuilder Model Cavity Space 0.50m	DesignBuilder Model Cavity Space 0.75m	DesignBuilder Model Cavity Space 1.00m	DesignBuilder Model Cavity Space 1.25m	DesignBuilder Model Cavity Space 1.50m
						

For each DF scenario six different simulations were done, documenting the energy performance of the module after the addition of the veranda space. Moreover, for each case, the first run was to record the thermal loads of the module, and the second run was to record the primary energy loads. The Thermal Loads refer to the amount of heat that must be supplied or removed from a thermal zone. Whereas the Primary Energy is the energy demand of a thermal zone which considers the thermal loads and the electricity efficiency of the HVAC system.

7.5 PV-Sites and Energy Production Calculations

For the Primary Energy consumptions, for the BIPV DF and the BIPV/T DF systems scenarios, the contribution of the Renewable Energy Resources was also calculated. The calculations were done for each month separately. To calculate the electricity production of the BIPV and the BIPV/T systems the following equation was considered:

PV Electric Energy Production (kWh) = PV Area (m^2) x Electricity Efficiency x Monthly Incident Solar Radiation (kWh/m²)

where:

PV & PV/T area = 5.25 m^2
Electrical Nominal Efficiency of PV Panels = 0.21

To record the monthly incident solar radiation, the software PV-Sites [81], was used. On tables A51 and A52 in Appendix section 10.3, the numerical values for each month are shown. Also, Figure A1 *in Appendix section 10.3*, illustrated the PV-Sites Model, and the distribution of Solar Radiation Levels on the South Elevation per month. Table 9, summarizes the monthly electricity production for the two systems BIPV and BIPV/T.

Table 9. Monthly Electricity Production for the two Systems BIPV and BIPV/T.

Electricity Production (kWh)												
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BIPV	105.84	102.53	108.05	108.05	97.57	84.89	92.06	110.25	131.20	138.36	118.52	109.15
BIPVT	126.00	122.06	128.63	128.63	116.16	101.06	109.59	131.25	156.19	164.72	141.09	129.94

Through this chapter, the module design and characteristics of the building envelope, geometry, dimensions, the HVAC system used and the environmental conditions under the module was examined were presented and analysed. Based on all the above assumptions and parameters, the results were recorded and will be represented in the following chapter.

8 RESUTLS AND DISCUSSION

Through this section, the results are presented through a series of graphs, as well as the discussion. The results were obtained using EnergyPlus dynamic simulation software through the platform DesignBuilder. All the results were documented for every month and then using graphical representation and tables, the different cavity depths for each DF systems were examined. Each DF system was evaluated by itself since the design conditions for each proposed DF system differ. The results are represented as Thermal Loads and as Primary Energy Consumptions. For each scenario, the results were compared to the reference case, meaning the module with no balcony. To evaluate the contribution by the BIPVs and the BIPVTs compared with the energy needs of the module, the energy consumptions of the module had to be converted into primary energy, using the primary energy factor (kWh/kWh) for electricity According to the document 'Cyprus Building Energy Performance Methodology' [82], the conversion and emissions factors of electricity for nZEB is 2.7.

8.1 Data Analysis and Discussion on Thermal Loads

8.1.1 Conventional DF

As mentioned, the first Double Façade system examined was a Conventional Double Façade, meaning that no PV system was integrated. The simulations were performed for all six different cavity depths starting from 0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m, and 1.50 m are shown in diagrams 1-3. Also, for the thermal loads evaluation, the module with no double façade was also included in the graphs. Starting from diagram 1, the Heating Thermal Loads for all the above cavity depths are presented. *For the monthly numerical values for the Conventional DF heating thermal loads, see Appendix 10.1 table A8.*

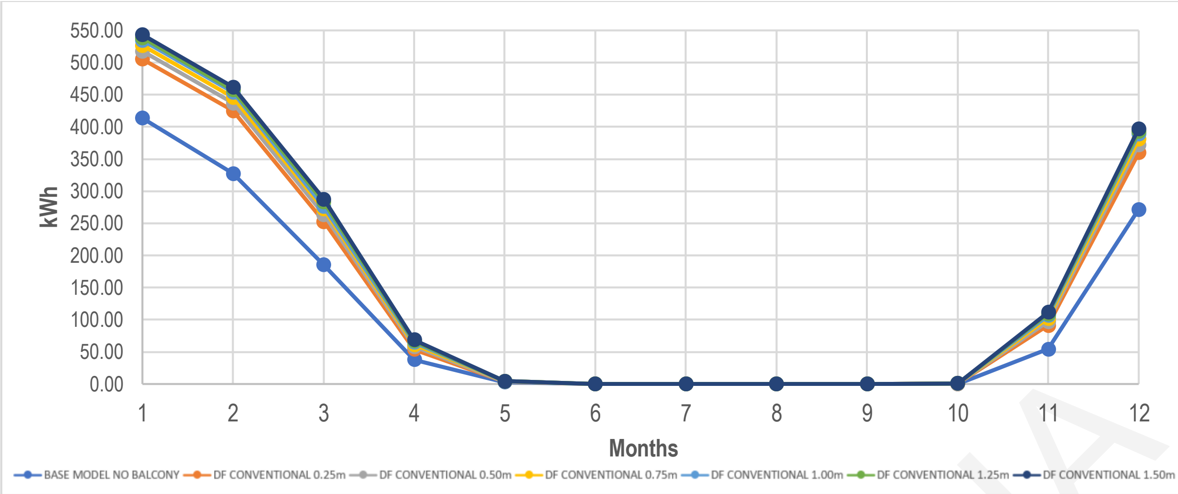


Diagram 1. Conventional DF_Heating Thermal Loads

The results show that as the cavity depth increases, the heating thermal loads increase as well. More specifically, the yearly heating thermal loads for the module with no DF are 1292.55 kWh, for the cavity depth 0.25 m 1691.68 kWh, for the 0.50 m 1750.68 kWh, for the 0.75 m 1793.44 kWh, for the 1.00 m 1829.66 kWh, for the 1.25 m 1853.29 kWh, and the 1.50 m 1875.98 kWh. This increase in the heating thermal loads happens due to the shading effect. During the winter period solar gains are favourable, however in this case, the cavity depth, meaning the veranda space, increases the shading effect. Not enough solar radiation is entering the living space of the module, thus more heating thermal load is needed to be supplied into the module.

Diagram 2 represents the Cooling Thermal Loads for the Conventional DF system. *For the monthly numerical values for the Conventional DF cooling thermal loads, see Appendix 10.1 table A9.*

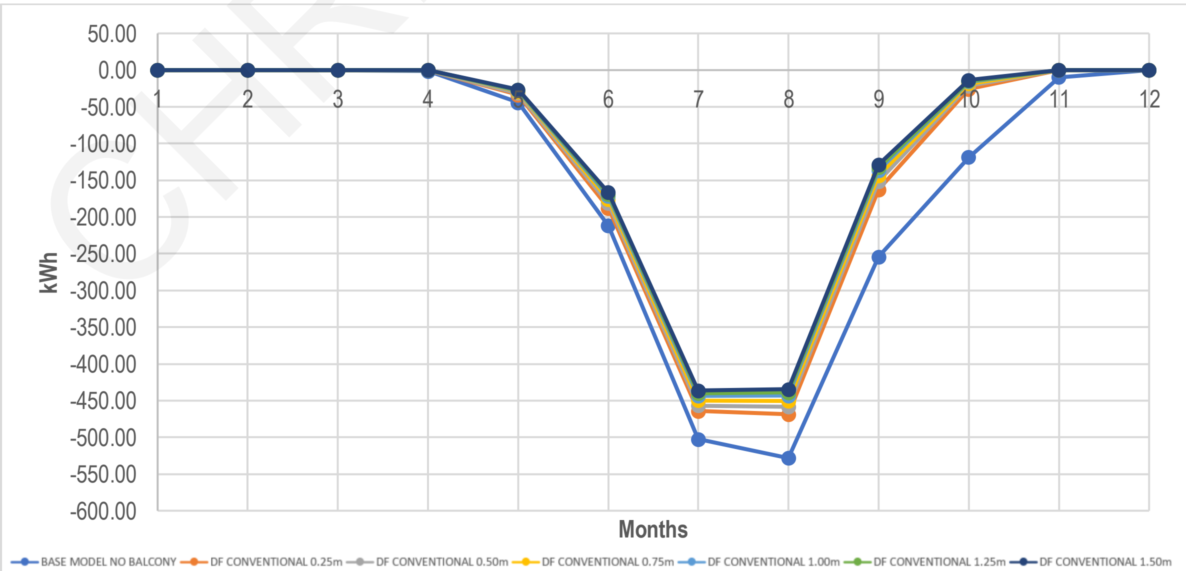


Diagram 2. Conventional DF_Cooling Thermal Loads

The results on Diagram 2, show that as the cavity depth increases, the cooling thermal loads decrease. The negative values on the graph mean that thermal loads must be extracted from the module. More specifically, the yearly cooling thermal loads for the module with no DF are -1671.35 kWh, for the cavity depth 0.25 m -1342.92 kWh, for the 0.50 m -1300.29 kWh, for the 0.75 m -1267.74 kWh, for the 1.00 m -1238.66 kWh, for the 1.25 m -1223.39 kWh, and the 1.50 m -1206.37 kWh. This decrease in the cooling thermal loads happens due to the shading effect, but this time the opposite happens. During the summer period solar gains are not favourable, and in this case, the cavity depth, meaning the veranda space, increases the shading effect, so again not enough solar radiation is entering the living space of the module, thus less thermal loads are needed to be extracted from the module.

Diagram 3 represents the Thermal Loads for the Conventional DF system. *For the monthly numerical values for the Conventional DF thermal loads, see Appendix 10.1 table A10.*

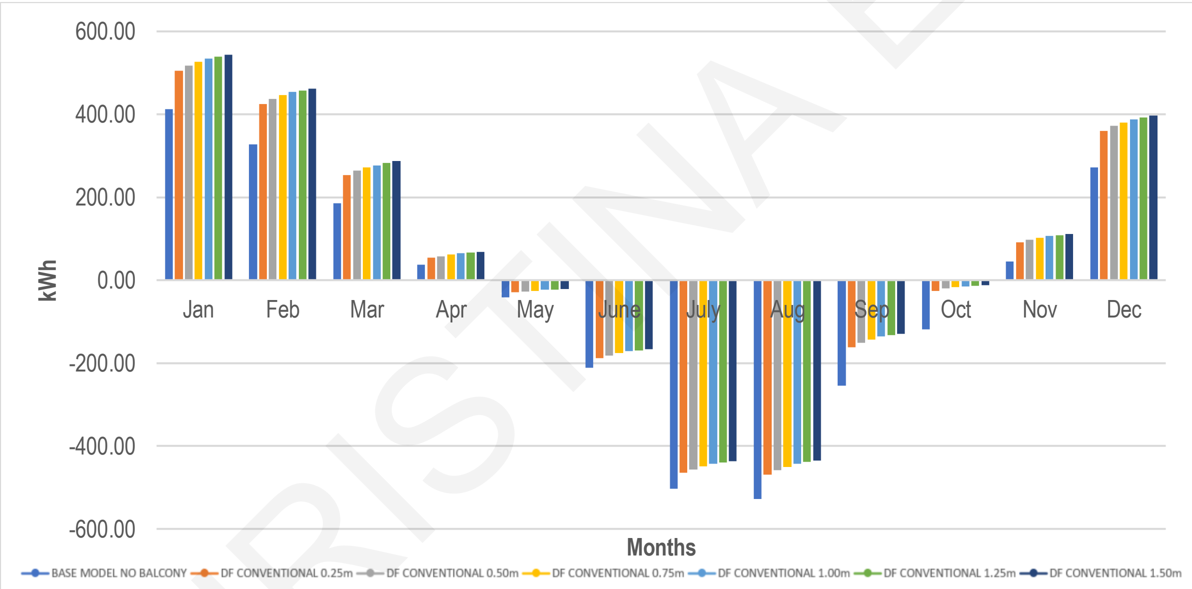


Diagram 3. Conventional DF_Thermal Loads

In diagram 3, the shading effect of the DF can be clearly observed, since during the winter period there is an increase in thermal loads as cavity depth increases, and during the summer period there is a decrease in the thermal loads as the cavity depth increases. The yearly thermal loads for the module with no DF are -378.80 kWh, for the cavity depth 0.25 m 348.76 kWh, for the 0.50 m 450.39 kWh, for the 0.75 m 525.70 kWh, for the 1.00 m 591.00 kWh, for the 1.25 m 629.90 kWh, and the 1.50 m 669.61 kWh. A parametric analysis of the heating and cooling loads was done to examine the optimum cavity depth conditions. Diagrams 4 and 5 illustrate the heating thermal loads and the cooling thermal loads for the Conventional DF. For the parametric analysis the yearly heating and cooling thermal loads results*, see Appendix 10.1 table A17,* were divided by the area of the module, 27.6 m^2.

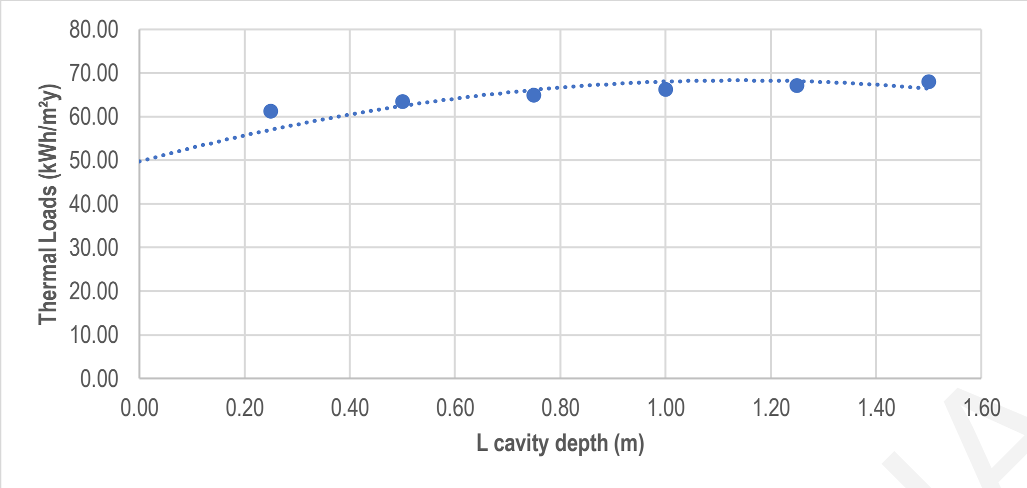


Diagram 4. Parametric Analysis, Conventional DF_Heating Thermal Loads

The yearly heating thermal loads per m[2] for the reference case is 46.83 kWh/m²y, 0.25 m cavity depth are 61.26 kWh/m²y, for the 0.50 m 63.43 kWh/m²y, for the 0.75 m 64.98 kWh/m²y, for the 1.00 m 66.29 kWh/m²y, for the 1.25 m 67.15 kWh/m²y, and for the 1.50 m 67.97 kWh/m²y. The trending line equation derived from the graph is the following:

$$Q_h = -14.3 \cdot L^2 + 32.592 \cdot L + 49.739$$

where:

Q_h = the heating thermal loads

L = cavity depth

L_{opt} = 1.14 m

In this case, the heating thermal loads the cavity depth which must be avoided is 1.14 m. Diagram 5, illustrates the parametric analysis done for the cooling thermal loads. *For the numerical values see Appendix 10.1 table A18.*

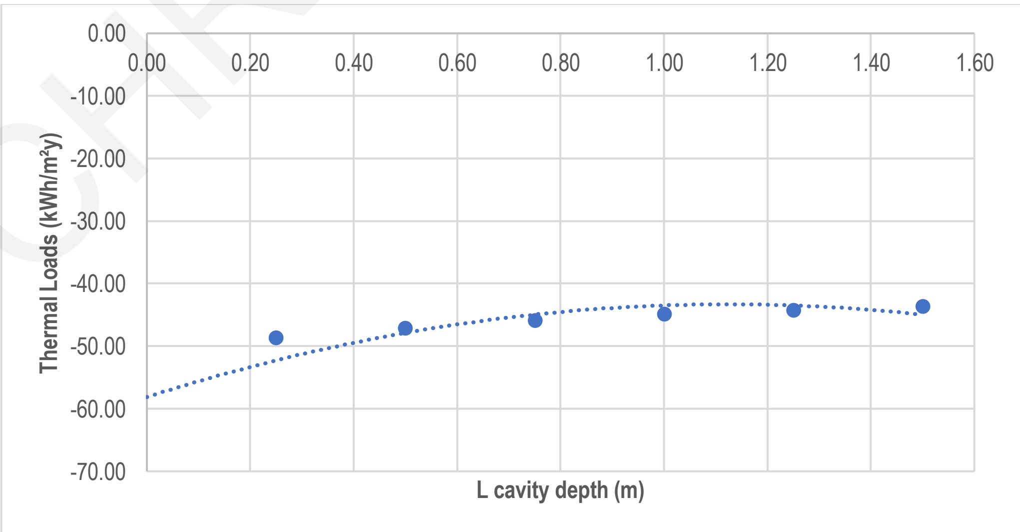


Diagram 5. Parametric Analysis, Conventional DF_Cooling Thermal Loads

The yearly cooling thermal loads per m² for the reference case is -60.56 kWh/m²y, the 0.25 m cavity depth are -48.66 kWh/m²y, for the 0.50 m -47.11 kWh/m²y, for the 0.75 m -45.93 kWh/m²y, for the 1.00 m -44.88 kWh/m²y, for the 1.25 m -44.33 kWh/m²y, and for the 1.50 m -43.71 kWh/m²y. Even though the trendline seems to open downwards, the cooling thermal loads have a negative value since there is an extraction of thermal loads. Using the following trending line equation

$$Q_c = -11.738 \cdot L^2 + 26.383 \cdot L - 58.132$$

where:

Q_c = the cooling thermal loads

L = cavity depth

L_{opt} = 1.12 m

the cavity depth in which the cooling loads seem to be the lowest is 1.12 m. After evaluating all the graphs and the parametric analysis of the different cavity depths for the Conventional DF, in terms of using the cavity depth as a veranda space, the ideal scenario of a Conventional DF to be used as a veranda space, is the 1.00 m cavity depth. The range between 0.25 m - 0.75 m is excluded since there is not enough liveable space.

8.1.2 BIPV Façade System

Secondly, the BIPV façade system was examined in terms of thermal loads. For these calculations, the BIPV electricity production was not included. The simulations were performed for all six different cavity depths starting from 0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m, and 1.50 m are shown in diagrams 6-8. Again, as the DF system, the module with no double façade was also included in the graphs. On diagram 4, the Heating Thermal Loads for all the above cavity depths are presented. *For the monthly numerical values for the BIPV DF heating thermal loads, see Appendix 10.1 table A17.*

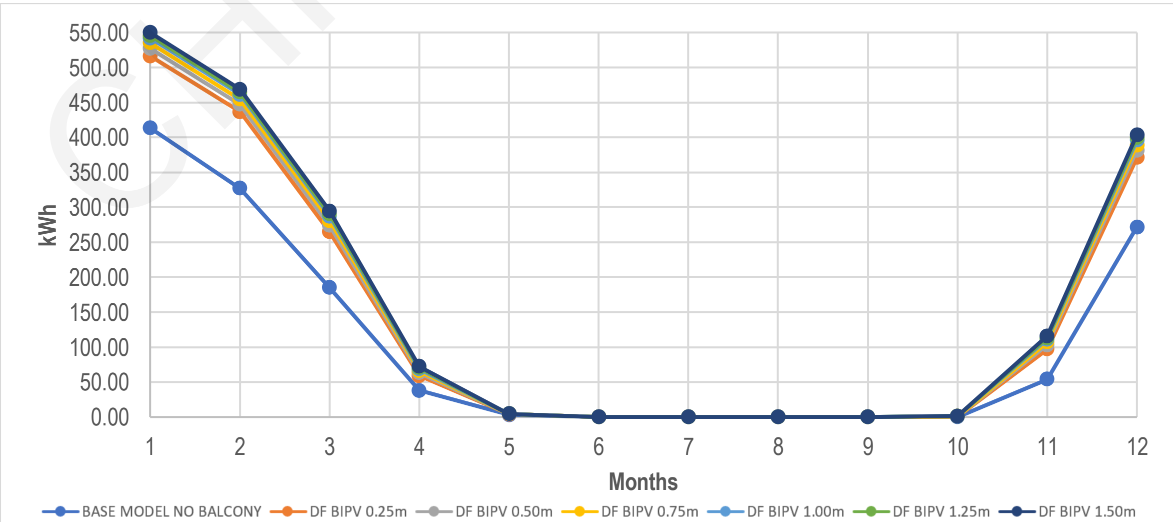


Diagram 6. BIPV DF_Heating Thermal Loads

As in the Conventional DF system, the results show that as the cavity depth increases, the heating thermal loads increase as well. More specifically, the yearly heating thermal loads for the module with no DF are 1292.55 kWh, for the cavity depth 0.25 m 1749.44 kWh, for the 0.50 m 1800.33 kWh, for the 0.75 m 1837.67 kWh, for the 1.00 m 1872.52 kWh, for the 1.25 m 1889.50 kWh, and the 1.50 m 1910.18 kWh. Once again, this increase in the heating thermal loads occurs because of the shading effect, in which during the winter period the cavity depth increases the shading effect and not enough solar radiation is entering the interior space, thus more heating thermal load is needed to be supplied into the module.

Diagram 7 represents the Cooling Thermal Loads for the BIPV DF system. *For the monthly numerical values for the BIPV DF cooling thermal loads, see Appendix 10.1 table A18.*

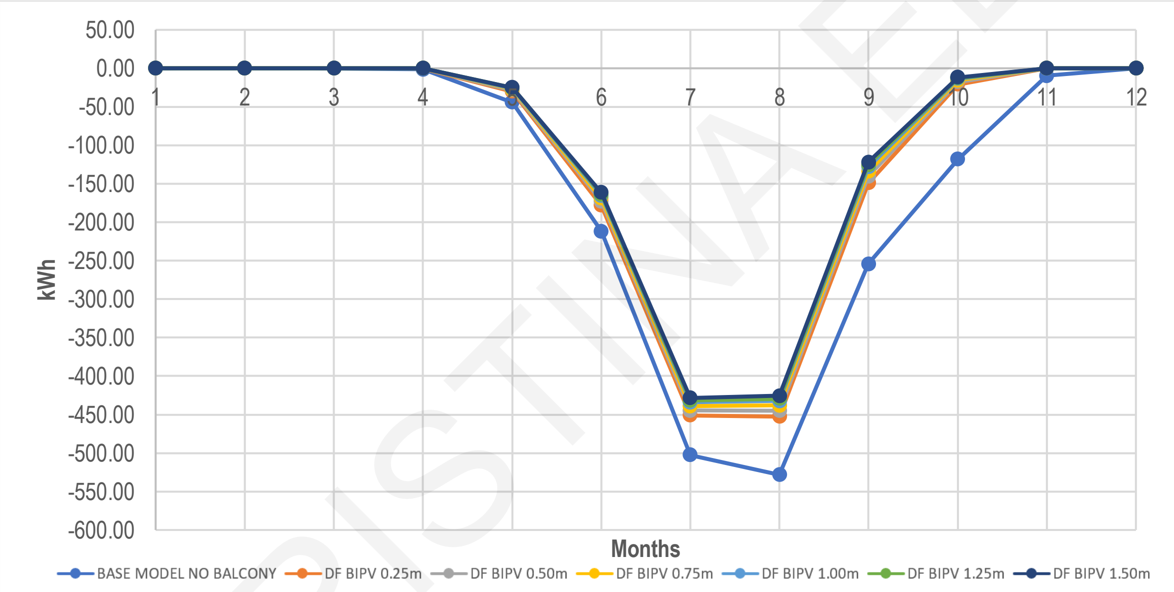


Diagram 7. BIPV DF_Cooling Thermal Loads

Diagram 7 shows that as the cavity depth increases, the cooling thermal loads decrease. Specifically, the yearly cooling thermal loads for the module with no DF are -1671.35 kWh, for the cavity depth 0.25 m -1281.79 kWh, for the 0.50 m -1249.09 kWh, for the 0.75 m -1222.98 kWh, for the 1.00 m -1198.84 kWh, for the 1.25 m -1188.54 kWh, and the 1.50 m -1174.22 kWh. Once again, this decrease in the cooling thermal loads occurs due to the shading effect, where during the summer period the cavity depth, increases the shading effect, not enough solar radiation is entering the living space of the module, thus less thermal loads are needed to be extracted from the module. Diagram 8 represents the Thermal Loads for the BIPV DF system. *For the monthly numerical values for the BIPV DF thermal loads, see Appendix 10.1 table A19.*

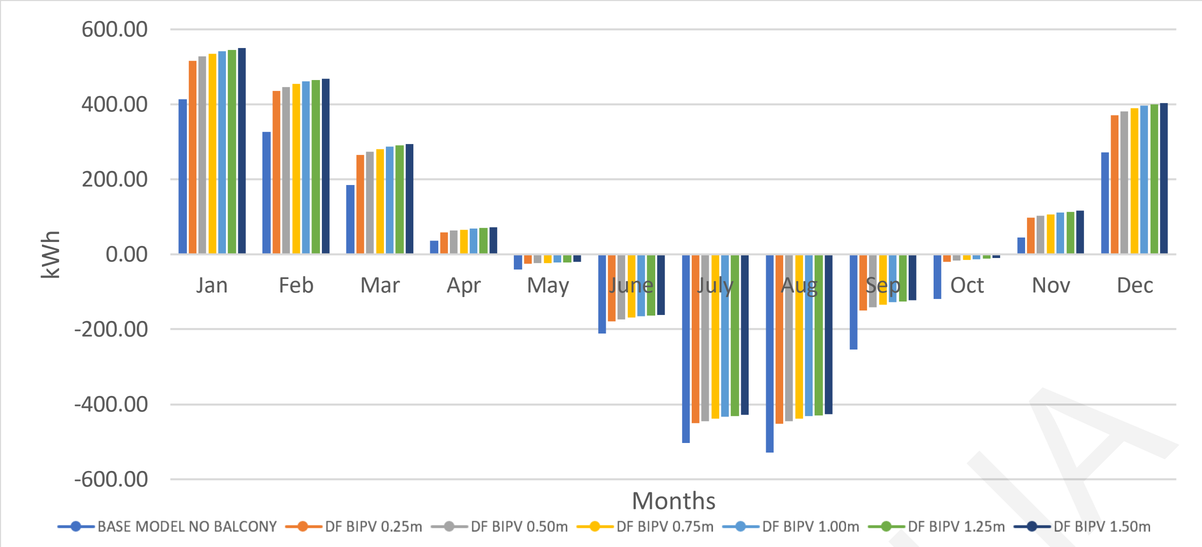


Diagram 8. BIPV DF_ Thermal Loads

As shown in diagram 8, during the winter period the heading thermal loads increase as cavity depth increases, whereas during the summer period as cavity depth increases the cooling thermal loads decrease. Specifically, the yearly thermal loads for the module with no DF are -378.80 kWh, for the cavity depth 0.25 m 467.65 kWh, for the 0.50 m 551.24 kWh, for the 0.75 m 614.69 kWh, for the 1.00 m 673.68 kWh, for the 1.25 m 700.96 kWh, and the 1.50 m 735.96 kWh.

A parametric analysis of the heating and cooling loads was also done, and the results are shown on diagrams 9 and 10. For the parametric analysis the yearly heating and cooling thermal loads results were divided by the area of the module, 27.6 m^2. *For the numerical values see Appendix 10.1 table A17.*

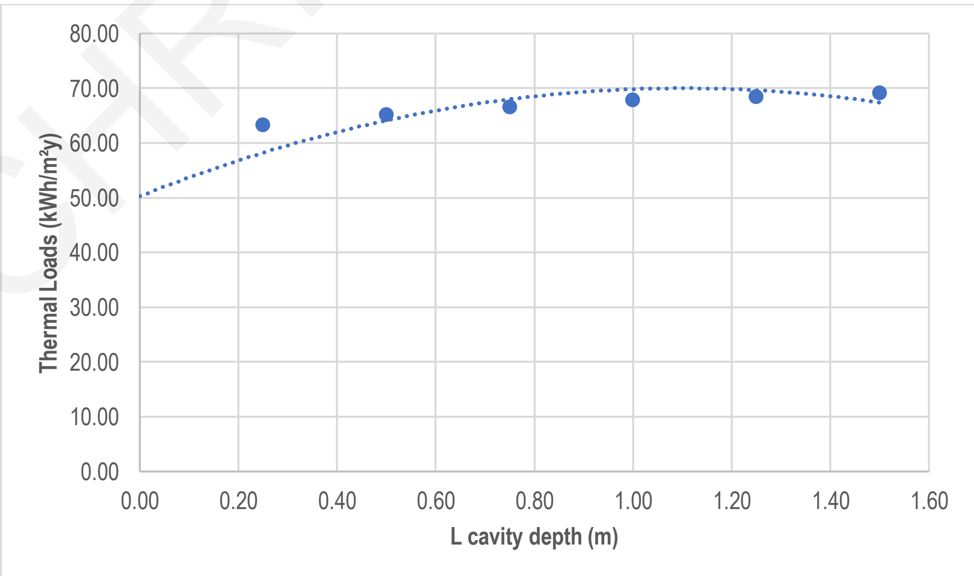


Diagram 9. Parametric Analysis, BIPV DF_Heating Thermal Loads

The yearly heating thermal loads per m2 for the reference case is 46.83 kWh/m²y, the 0.25 m cavity depth are 63.39 kWh/m²y, for the 0.50 m 65.23 kWh/m²y, for the 0.75 m 66.58 kWh/m²y, for the 1.00 m 67.84 kWh/m²y, for the 1.25 m 68.46 kWh/m²y, and for the 1.50 m 69.21 kWh/m²y. The trending line equation derived from the graph is the following:

$$Q_h = -16.257 \cdot L^2 + 35.799 \cdot L + 50.294$$

L_{opt} = 1.10 m

In this case, the heating thermal loads the cavity depth which must be avoided is 1.10 m. Diagram 10, illustrates the parametric analysis done for the cooling thermal loads. *For the numerical values see Appendix 10.1 table A18.*

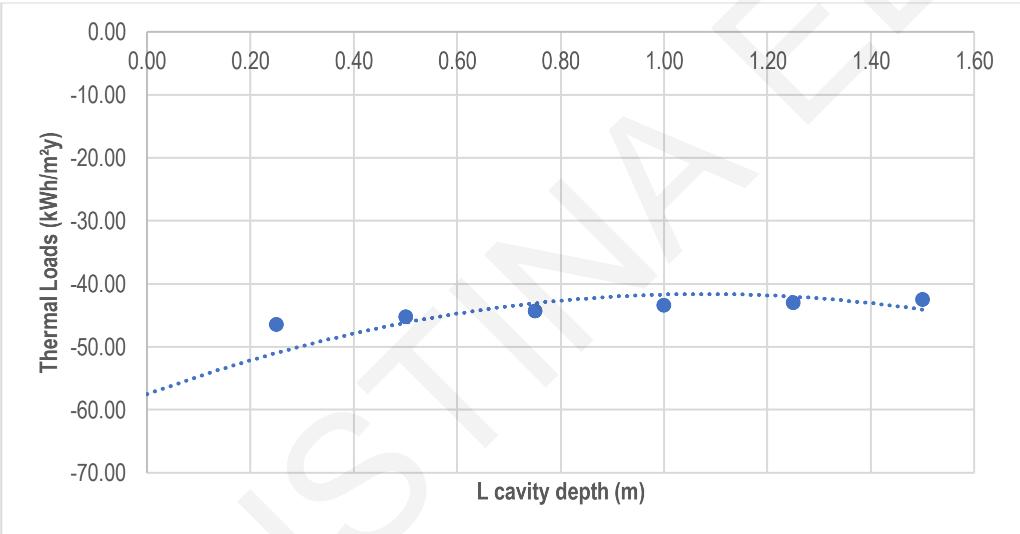


Diagram 10. Parametric Analysis, BIPV DF_ Cooling Thermal Loads

The yearly cooling thermal loads per m2 for the reference case is -60.56 kWh/m²y, for the 0.25 m cavity depth are -46.44 kWh/m²y, for the 0.50 m -45.26 kWh/m²y, for the 0.75 m -44.31 kWh/m²y, for the 1.00 m -43.44 kWh/m²y, for the 1.25 m -43.06 kWh/m²y, and for the 1.50 m -42.54 kWh/m²y. Even though the trendline seems to open downwards, the cooling thermal loads have a negative value since there is an extraction of thermal loads. Using the following trending line equation

$$Q_c = -13.748 \cdot L^2 + 29.567 \cdot L - 57.521$$

L_{opt} = 1.08 m

the cavity depth in which the cooling loads seem to be the lowest is 1.08 m. After evaluating all the graphs and the parametric analysis of the different cavity depths for the BIPV DF, in terms of using the cavity depth as a veranda space, the ideal scenario of the BIPV DF to be used as a veranda space, is 1.00 m cavity depth. As said the range between 0.25 m - 0.75 m is excluded since there is not enough liveable space.

8.1.3 BIPV/T Façade System

Lastly the BIPV/T DF system was evaluated in terms of thermal loads. The simulations were performed for all six different cavity depths starting from 0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m, and 1.50 m are shown on diagrams 11-13. As in the other two scenarios for the thermal loads evaluation, the module with no double façade was also included in the graphs. In diagram 11, the Heating Thermal Loads for all the above cavity depths are presented. *For the monthly numerical values for the BIPV/T DF heating thermal loads, see Appendix 10.1 table A26.*

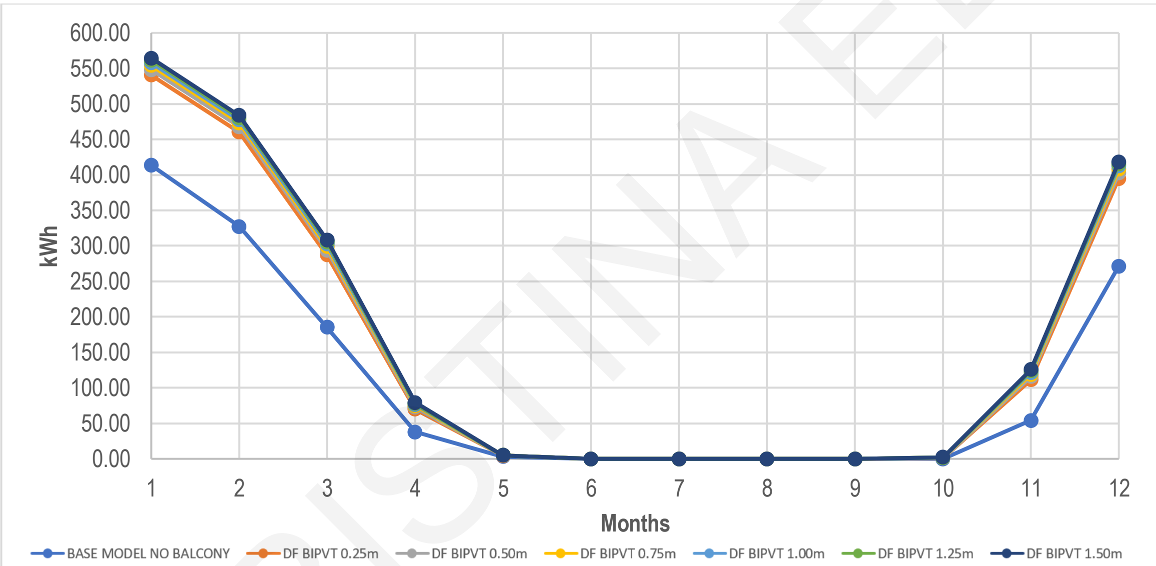


Diagram 11. BIPV/T DF_Heating Thermal Loads

As in the other two DF scenarios, the results show that as the cavity depth increases, the heating thermal loads increases as well. More specifically, the yearly heating thermal loads for the module with no DF are 1292.55 kWh, for the cavity depth 0.25 m 1869.35 kWh, for the 0.50 m 1906.46 kWh, for the 0.75 m 1934.38 kWh, for the 1.00 m 1954.35 kWh, for the 1.25 m 1972.13 kWh, and the 1.50 m 1986.21 kWh. Once again, this increase in the heating thermal loads occurs because of the shading effect, in which during the winter period the cavity depth increases the shading effect and not enough solar radiation is entering the interior space, thus more heating thermal load is needed to be supplied into the module.

Diagram 12 represents the Cooling Thermal Loads for the BIPV/T DF system. *For the monthly numerical values for the BIPV/T DF cooling thermal loads, see Appendix 10.1 table A27.*

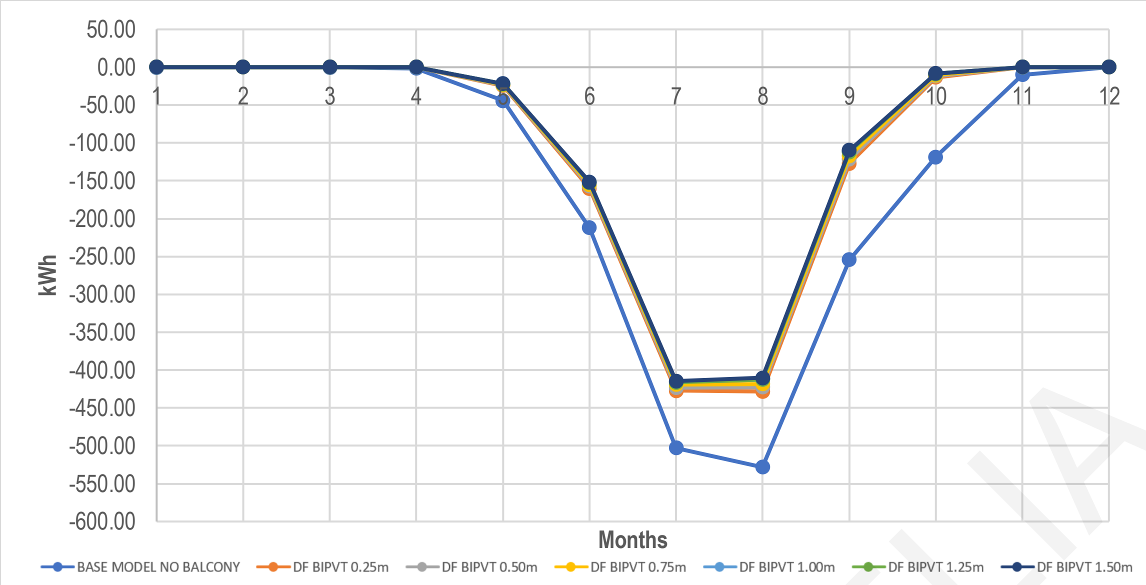


Diagram 12. BIPV/T DF_Cooling Thermal Loads

Diagram 12 shows that as the cavity depth increases, the cooling thermal loads decrease. Specifically, the yearly cooling thermal loads for the module with no DF are -1671.35 kWh, for the cavity depth 0.25 m -1180.53 kWh, for the 0.50 m -1159.46 kWh, for the 0.75 m -1142.75 kWh, for the 1.00 m -1121.33 kWh, for the 1.25 m -1123.73 kWh, and the 1.50 m -1116.24 kWh. As the previous scenarios, this decrease in the cooling thermal loads occurs due to the shading effect, where during the summer period the cavity depth, increases the shading effect, not enough solar radiation is entering the living space of the module, thus less thermal loads are needed to be extracted from the module.

Diagram 13 represents the Thermal Loads for the BIPV/T DF system. *For the monthly numerical values for the BIPV/T DF thermal loads, see Appendix 10.1 table A28.*

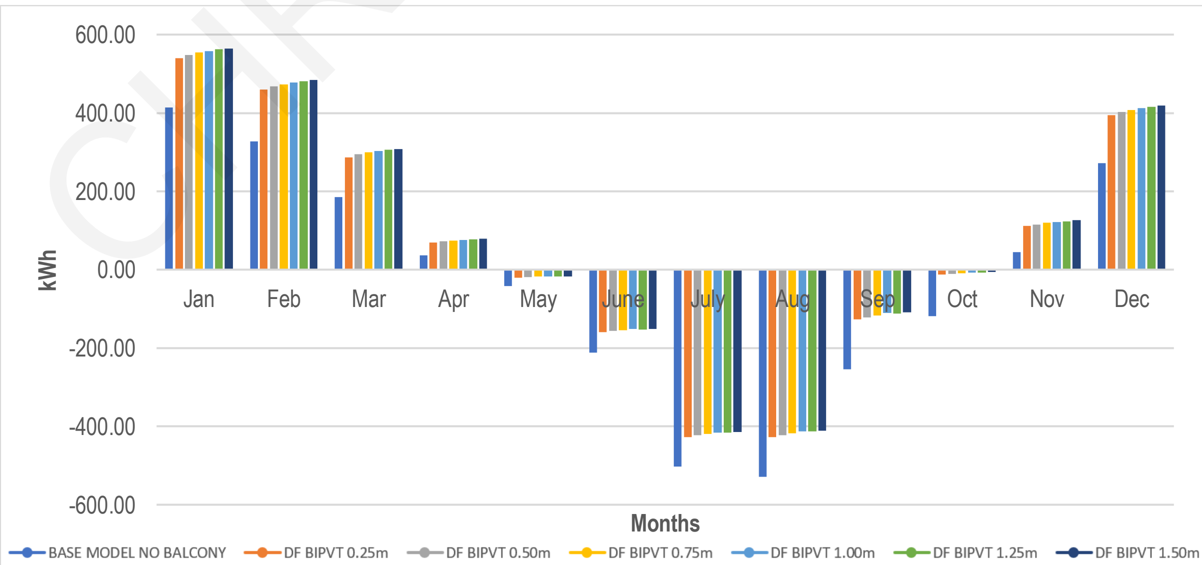


Diagram 13. BIPV/T DF_ Thermal Loads

As shown in diagram 8, during the winter period the heating thermal loads increase as cavity depth increases, whereas during the summer period as cavity depth increases the cooling thermal loads decrease. Specifically, the yearly thermal loads for the module with no DF are -378.80 kWh, for the cavity depth 0.25 m 688.82 kWh, for the 0.50m 747.00 kWh, for the 0.75 m 791.63 kWh, for the 1.00 m 833.02 kWh, for the 1.25 m 848.40 kWh, and for the 1.50 m 869.07 kWh.

As in the other two scenarios, a parametric analysis of the heating and cooling loads was also done, and the results are shown on diagrams 14 and 15. For the parametric analysis the yearly heating and cooling thermal loads results were divided by the area of the module, 27.6 m^2. *For the numerical values see Appendix 10.1 table A26.*

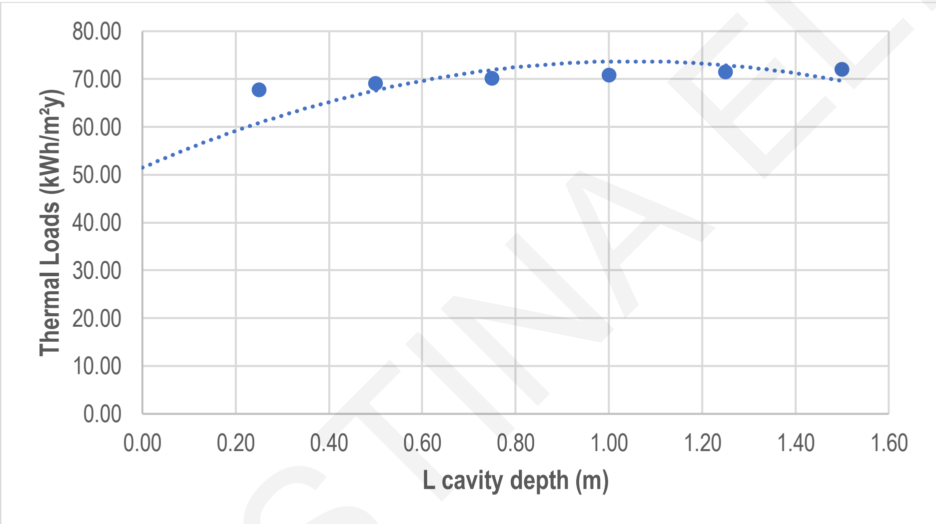


Diagram 14. Parametric Analysis, BIPV/T DF_Heating Thermal Loads

The yearly heating thermal loads per m^2 for the reference case is 46.83 kWh/m²y, for the 0.25 m cavity depth are 67.73 kWh/m²y, for the 0.50 m 69.07 kWh/m²y, for the 0.75 m 70.09 kWh/m²y, for the 1.00 m 70.81 kWh/m²y, for the 1.25 m 71.45 kWh/m²y, and for the 1.50 m 71.96 kWh/m²y. The trending line equation derived from the graph is the following:

$$Q_h = -20.194 \cdot L^2 + 42.374 \cdot L + 51.477$$

L_{opt} = 1.05 m

In this case, the heating thermal loads the cavity depth which must be avoided is 1.05 m. Diagram 15, illustrates the parametric analysis done for the cooling thermal loads. *For the numerical values see Appendix 10.1 table A27.*

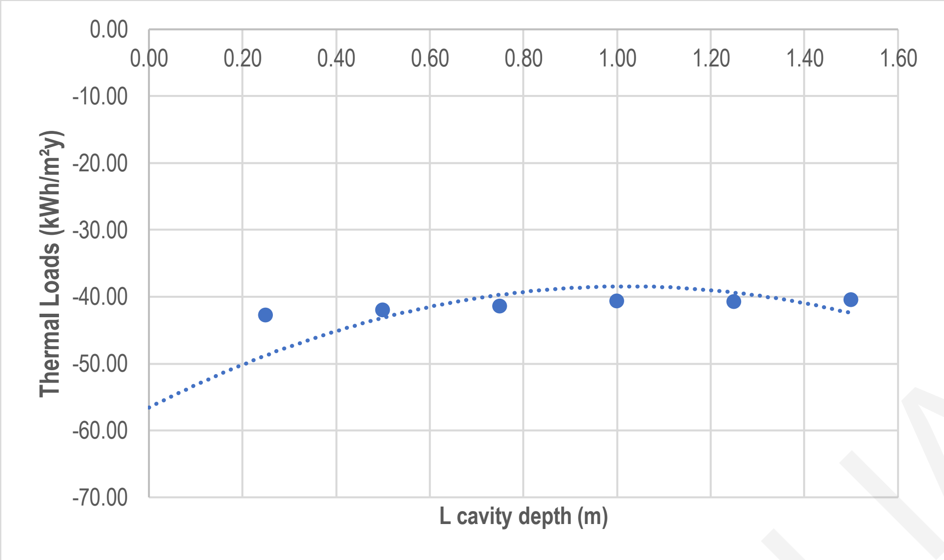


Diagram 15. Parametric Analysis, BIPV/T DF_Cooling Thermal Loads

The yearly cooling thermal loads per m² for the reference case is -60.56 kWh/m²y, for the 0.25 m cavity depth are -42.77 kWh/m²y, for the 0.50 m -42.01 kWh/m²y, for the 0.75 m -41.40 kWh/m²y, for the 1.00 m -40.63 kWh/m²y, for the 1.25 m -40.71 kWh/m²y, and for the 1.50 m -40.44 kWh/m²y. Even though the trendline seems to open downwards, the cooling thermal loads have a negative value since there is an extraction of thermal loads. Using the following trending line equation

$$Q_c = -17.423 \cdot L^2 + 35.539 \cdot L - 56.574$$

$L_{opt} = 1.02$ m

the cavity depth in which the cooling loads seem to be the lowest is 1.02 m. After evaluating all the graphs and the parametric analysis of the different cavity depths for the BIPV/T DF, in terms of using the cavity depth as a veranda space, the ideal scenario of the BIPV/T DF to be used as a veranda space, is the 1.00 m cavity depth. As said the range between 0.25 m - 0.75 m is excluded since there is not enough liveable space.

8.2 Data Analysis and Discussion on Primary Energy Consumptions

As described in section 7.5. to calculate the electricity production of the BIPV and the BIPV/T systems the PV sites software was used. The solar radiance value per m² was recorded and the results of the electricity production were shown on table 9 section 7.5. To be able to calculate the contribution on the primary energy demands of these two systems, the results were multiplied by 2.7 to be converted into primary energy. According to the 'Cyprus Building Energy Performance Methodology' [82], 2.7 is the

Primary Energy Factor (kWh/kWh) used for electricity from the grid, to evaluate the energy needs for nZEB. On table 10, the conversion of BIPV and BIPV/T electricity production in primary energy is shown.

Table 10. Summarized Primary Energy Production per Month for the two Systems BIPV and BIPV/T.

	Primary Energy Electricity Production (kWh)											
	Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
BIPV	285.77	276.84	291.72	291.72	263.44	229.21	248.56	297.68	354.23	373.58	320.00	294.70
BIPVT	340.20	329.57	347.29	347.29	313.62	272.87	295.90	354.38	421.71	444.74	380.95	350.83

A parametric analysis was done for the Primary Energy Consumptions for each proposed DF system to find the optimum cavity depth and the minimum energy consumption levels that the proposed PV and PV/T systems can achieve. The Primary Energy needs were evaluated in terms of the different cavity depth for each scenario. In the following diagrams, the contribution of the BIPV and the BIPV/T electricity production is taken into consideration for the equivalent proposed DF systems.

8.2.1 Conventional DF

Starting with the Conventional DF system, the Primary Energy Needs were calculated and recorded for each month, and then the yearly consumption needs were divided by the module's square meters to normalise the Primary Energy needs to nZEB. Since there was no PV system integrated in this scenario, the Primary Energy readings take account only of the module itself. The module with no double façade was also included in the graphs. Diagram 16 represents the parametric analysis of the Primary Energy Needs for the Conventional DF. *For the monthly numerical values for the Conventional DF Primary Energy Needs, see Appendix 10.2 tables A30-36.*

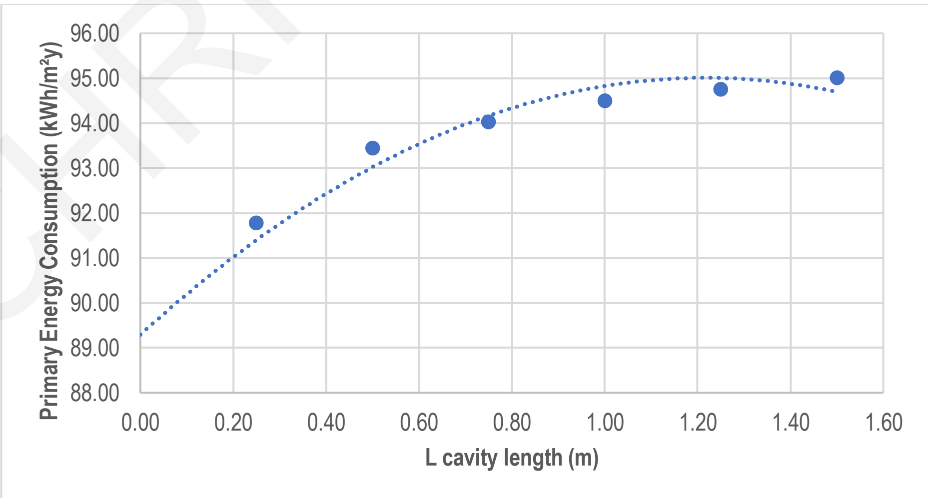


Diagram 16. Parametric Analysis, Conventional DF_Primary Energy Needs

The yearly Primary Energy Needs per m^2 for the reference case is 88.93 kWh/m²y, for the 0.25 m cavity depth are 91.77 kWh/m²y, for the 0.50 m 93.44 kWh/m²y, for the 0.75 m 94.03 kWh/m²y, for the 1.00 m 94.49 kWh/m²y, for the 1.25 m 94.74 kWh/m²y, and for the 1.50 m 95.00 kWh/m²y. As the cavity depth increases the Primary Energy Needs increases as well. As discussed in section 8.1.1, this occurs because the heating energy demands for the module are higher due to the shading effect. Even though the cooling energy needs are decreasing, it was observed that the rate in which heating energy needs were increasing, is higher than the decrease rate of the cooling energy needs. Using the following trending line equation which derived from Diagram 16, the cavity depth with the highest Primary Energy Needs was recorded.

$$PE = -3.8542 \cdot L^2 + 9.386 \cdot L + 89.292$$

L_{opt} = 1.22 m

In this case, in terms of Primary Energy Needs, the cavity depth which must be avoided is 1.22 m. After evaluating all the graphs and the parametric analysis of the different cavity depths for the Conventional DF, in terms of using the cavity depth as a veranda space, the ideal scenario for this DF system to be used as a veranda space, is again the 1.00m cavity depth. As said the range between 0.25 m - 0.75 m is excluded since there is not enough liveable space.

8.2.2 BIPV Façade System

The Primary Energy Needs for the proposed BIPV DF system were calculated and recorded for each month, and then the yearly consumption needs were divided by the module's square meters to normalise the Primary Energy needs to nZEB. In this scenario, the contribution of the PV system electricity production was incorporated in the results. As mentioned, the PV electricity production were converted into Primary Energy Needs. The module with no double façade was also included in the graphs. Diagram 17 represents the parametric analysis of the Primary Energy Needs for the BIPV DF. *For the monthly numerical values for the BIPV DF Primary Energy Needs, see Appendix 10.2 tables A37-43.*

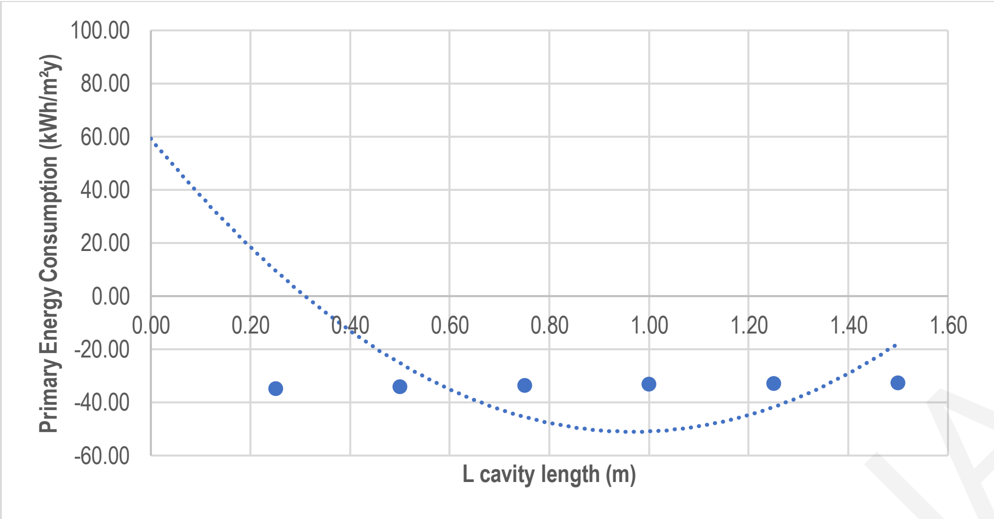


Diagram 17. Parametric Analysis, BIPV DF_Primary Energy Needs

The yearly Primary Energy Needs per m^2 for the reference case is 88.93 kWh/m^2y, for the 0.25 m cavity depth are -34.83 kWh/m^2y, for the 0.50 m -34.07 kWh/m^2y, for the 0.75 m -33.58 kWh/m^2y, for the 1.00 m -33.12 kWh/m^2y, for the 1.25 m -32.86 kWh/m^2y, and for the 1.50 m -32.59 kWh/m^2y. The results show that the integration of BIPVs has a positive contribution in lowering the Primary Energy demands. The electric energy produced form the BIPV system, for most of the months, is enough to cover the entire electricity needs of the module, *see Appendix 10.2 Table A43.* Using the trending line equation which derived from Diagram 17, the optimum cavity depth was recorded.

$$PE = 117.64 \cdot L^2 - 227.83 \cdot L + 59.279$$

$L_{opt} = 0.97$ m

The optimum cavity depth to achieve the optimum Primary Energy Needs is calculated to be 0.97 m. Apart from the optimum cavity depth, the optimum Primary Energy Needs with the optimum BIPV electricity production, were calculated using the following equation:

$$PE_{opt} = -51.03 \ kWh/m^2y$$

As a conclusion, the optimum cavity depth derived from the results, 0.97 m, can be used as a semi-open veranda space as an extension to the living space. Having this cavity depth, the BIPV system will also produce electricity at its highest efficiency rate this being -51.03 kWh/m^2y.

8.2.3 *BIPV/T Façade System*

Lastly, the Primary Energy Needs for the proposed BIPV/T DF system were calculated and recorded for each month, and then the yearly consumption needs were divided by the module's square meters to normalise the Primary Energy needs to nZEB. In this scenario, the contribution of the PV/T system to electricity production was incorporated in the results. As mentioned, the PV/T electricity production was converted into Primary Energy Needs. The module with no double façade was also included in the graphs. Diagram 18 represents the parametric analysis of the Primary Energy Needs for the BIPV/T DF. *For the monthly numerical values for the BIPV/T DF Primary Energy Needs, see Appendix 10.2 tables A44-50.*

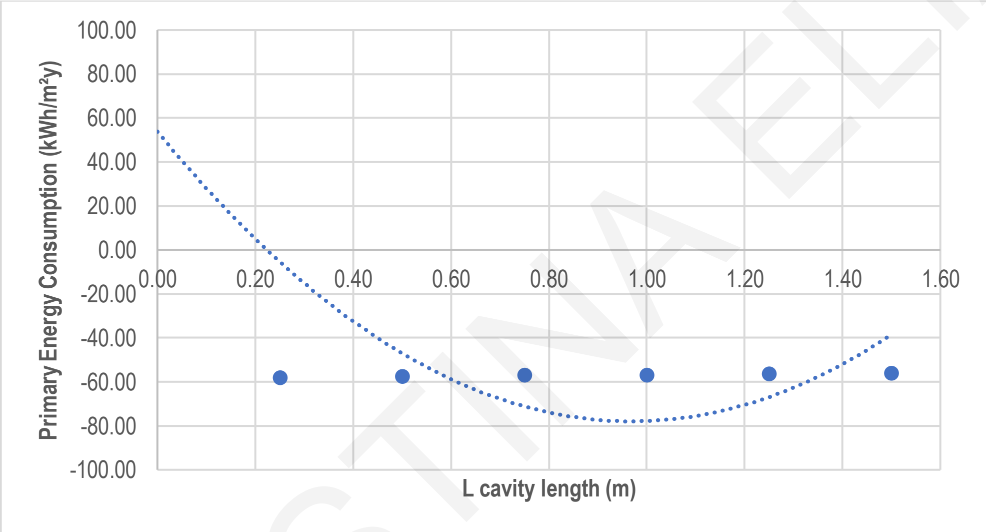


Diagram 18. Parametric Analysis, BIPV/T DF_Primary Energy Needs

The yearly Primary Energy Needs per m^2 for the reference case is 88.93 kWh/m²y, for the 0.25 m cavity depth are -58.09 kWh/m²y, for the 0.50 m -57.47 kWh/m²y, for the 0.75 m -57.01 kWh/m²y, for the 1.00 m -56.96 kWh/m²y, for the 1.25 m -56.33 kWh/m²y, and for the 1.50 m -56.08 kWh/m²y. The results show that the integration of BIPV/Ts has a positive contribution in lowering the Primary Energy demands. The electric energy produced form the BIPV/T system, for most of the months, is enough to cover the entire electricity needs of the module, *see Appendix 10.2 Table A50.* Using the trending line equation which derived from Diagram 17, the optimum cavity depth was recorded.

$$PE = 140.11 \cdot L^2 - 271.73 \cdot L + 53.816$$

$L_{opt} = 0.97$ m

The optimum cavity depth to achieve the optimum Primary Energy Needs is calculated to be 0.97m. Apart from the optimum cavity depth, the optimum Primary Energy Needs with the optimum BIPV/T electricity production, were calculated using the following equation:

$$PE_{opt} = -77.93 \text{ kWh/m}^2\text{y}$$

As a conclusion, the optimum cavity depth derived from the results for the BIPV/T DF is 0.97 m. This cavity depth can be used as a semi-open veranda space and an extension of the living space. Having this cavity depth, the BIPV/T system will also produce electricity at its highest efficiency rate, this being -77.93 kWh/m²y.

In this chapter, the results were presented and discussed through a series of diagrams and references to numerical tables. For each DF system mentioned, the optimum cavity depth was proposed after considering the aforementioned parameters. Lastly, the Primary Energy Needs calculations, highlighted the importance of integrating Renewable Energy Sources.

9 CONCLUSION AND FUTURE RESEARCH

In this research, the contribution of three proposed DF systems in terms of Thermal Loads and Primary Energy Needs was presented and analysed using quantitative methods and visualisations. The three DF systems were a Conventional DF, a BIPV DF and a BIPV/T DF. For each scenario, the parameter that was varying was the cavity depth. The six different cavity depths examined were 0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m, and 1.50 m. Apart from the Thermal Loads and the Primary Energy Needs, the cavity depth was also examined as to the extent to which it can be used as a semi-open veranda space, an extension to the living space. Documenting to what extent the contribution of the BIPV and the BIPV/T - in terms of integrating Renewable Energy Sources on a building, and in combination with which cavity depth -offers the most positive impact on the energy performance of the module, was this research ultimate aim. The scenarios were modelled and simulated using the EnergyPlus dynamic simulation software through the DesignBuilder platform. The module was examined using the Nicosia, Cyprus weather file and the module was treated as if it was placed in a multi-storey apartment block.

The results of the Thermal Loads simulations for all three proposed DF scenarios, showed that as the cavity depth increased, the Heating Thermal Loads increased as well. For the Cooling Thermal Loads, as the cavity depth increased the Cooling Thermal Loads decreased. As explained, as the cavity depth increases, the shading effect increases as well, meaning that during the winter period not enough solar radiation is entering the internal spaces. Thus, more Thermal Loads in the form of heating must be supplied into the module. Whereas during the summer period, because of the shading effect, there are less solar gains, thus the Cooling Thermal Loads decrease, fewer thermal loads must be extracted from the module. For a more detailed evaluation, a parametric analysis was also done, where the exact cavity dimension was calculated. This calculation can determine in terms of Heating Thermal Loads which one cavity depth to avoid and for Cooling Thermal Loads which cavity dimension is the optimum. After evaluating all results, the proposed cavity depth dimension for the Conventional DF, BIPV DF, and BIPV/T was set to be 1.00 m. Having 1.00 m cavity depth the Thermal Loads as not as high as having a higher depth, but at the same time it can be used as a veranda space, whereas 0.25 m-0.75 m cannot.

Moving on, a parametric analysis of the Primary Energy Needs, showed that for the Conventional DF system as the cavity depth increases, the Primary Energy needs increase as well, concluding that for the cavity space to have the minimum Primary Energy needs and used as a veranda space, the cavity depth should be set at 1.00 m. For the BIPV DF, and the BIPV/T DF system, the parametric analysis of the Primary Energy Needs, showed that the integration of PVs and PV/Ts, have a positive impact on lowering the Energy Needs. More specifically for the BIPV DF the optimum cavity depth was calculated to be 0.97 m with the optimum Energy Performance -51.03 kWh/m²y. For the BIPV/T DF, the optimum cavity depth was also calculated to be 0.97m with an optimum Energy Performance -77.93 kWh/m²y. The proposed cavity depth 0.97 m can be used as a veranda space as well.

The results showed that with the addition of a Conventional DF system it is not possible to lower the energy needs. Whereas with the implementation of a BIPV and a BIPV/T DF system, lowering the energy needs is possible. Both BIPV and BIPV/T DF systems, can contribute in achieving a building with very high energy performance, nZEB. The results of the contribution of the BIPV and the BIPV/T DF systems in terms of Primary Energy Savings, come to agree with Li [59], Peng [60], Piratheepan [62], Panao [65] et al., which stated that both BIPV and BIPV/T systems can lower the needs for energy and by incorporating them into the building envelope it can lead to nZEB. In a theoretical aspect of view, characterising the cavity depth as an outdoor-indoor space, it can also improve the quality of living, incorporate greenery into the design and improving the amount of natural lighting.

Future research looks to evaluate more parameters of the investigated module such as changing the height of the cavity depth. Moreover, an analysis in terms of sensitivity, the thermal comfort of the user in comparison the energy consumptions can also be investigated. The final aim is to compare and determine the optimum cavity depth conditions and dimensions in terms of energy savings, thermal comfort and for it to be able to be used as a semi-open veranda space extension to the living space.

Appendix

10 APPENDIX

In this section, the numerical values for the thermal loads and primary energy calculations are presented. The tables show the numerical values for each month per scenario, as documented through the DesignBuilder Software. Also, the electricity production calculations of the BIPV and BIPVT systems are presented, as well as the solar radiation values as documented on the PV Sites Software.

10.1 Thermal Loads Results

Table A1. Base Model No Balcony Thermal Loads.

A1. BASE MODEL NO BALCONY THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.57	15.87	17.57	17.01	17.57	17.01	17.57	17.57	17.01	17.57	17.01	17.57
Heating	kWh	**413.47**	**327.20**	**185.22**	**37.93**	**3.11**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**54.19**	**271.43**
Cooling	kWh	**-0.26**	**0.00**	**-0.10**	**-1.37**	**-44.26**	**-211.86**	**-502.73**	**-528.29**	**-254.14**	**-118.44**	**-9.90**	**0.00**
DHW	kWh	307.12	277.40	307.12	297.22	307.12	297.22	307.12	307.12	297.22	307.12	297.22	307.12

Tables A2-A7. Conventional DF System Cavity Depth 0.25 m – 1.50 m Thermal Loads

A4. DF CONVENTIONAL Veranda Depth 0.75m THERMAL													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**526.64**	**445.88**	**271.88**	**61.47**	**4.22**	**0.00**	**0.00**	**0.00**	**0.00**	**0.78**	**102.00**	**380.57**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-29.51**	**-176.31**	**-449.69**	**-450.55**	**-143.38**	**-18.30**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A2. DF CONVENTIONAL DF Depth 0.25m THERMAL													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**505.19**	**424.79**	**252.80**	**53.80**	**3.89**	**0.00**	**0.00**	**0.00**	**0.00**	**0.42**	**90.98**	**359.81**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**-0.10**	**-33.62**	**-187.90**	**-464.39**	**-468.61**	**-162.56**	**-25.74**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A3. DF CONVENTIONAL DF Depth 0.50m THERMAL													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**517.79**	**437.14**	**263.75**	**58.05**	**4.07**	**0.00**	**0.00**	**0.00**	**0.00**	**0.62**	**97.20**	**372.06**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**-0.02**	**-31.34**	**-181.42**	**-456.66**	**-458.42**	**-151.18**	**-21.25**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A5. DF CONVENTIONAL Veranda Depth 1.00m THERMAL													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**534.61**	**453.74**	**276.26**	**64.73**	**4.35**	**0.00**	**0.00**	**0.00**	**0.00**	**0.94**	**106.53**	**388.50**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-27.93**	**-171.67**	**-443.62**	**-443.18**	**-136.42**	**-15.84**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A6. DF CONVENTIONAL Veranda Depth 1.25m THERMAL													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**538.86**	**457.53**	**283.18**	**66.55**	**4.44**	**0.00**	**0.00**	**0.00**	**0.00**	**1.03**	**108.91**	**392.79**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-27.31**	**-169.40**	**-440.11**	**-439.05**	**-132.75**	**-14.77**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A7. DF CONVENTIONAL Veranda Depth 1.50m THERMAL													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**543.36**	**462.05**	**287.53**	**68.59**	**4.53**	**0.00**	**0.00**	**0.00**	**0.00**	**1.15**	**111.56**	**397.21**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-26.51**	**-166.73**	**-436.23**	**-434.57**	**-128.83**	**-13.50**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

Table A8. Conventional DF Heating Thermal Loads per Square Meters Yearly.

A8. Conventional DF Heating (Thermal Loads) (kWh)													SUM / square metres yearly (kWh/m^2y)
Cavity Length (m)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
NO BALCONY	413.47	327.20	185.22	37.93	3.11	0.00	0.00	0.00	0.00	0.00	54.19	271.43	**46.83**
0.25m	505.19	424.79	252.80	53.80	3.89	0.00	0.00	0.00	0.00	0.42	90.98	359.81	**61.29**
0.50m	517.79	437.14	263.75	58.05	4.07	0.00	0.00	0.00	0.00	0.62	97.20	372.06	**63.43**
0.75m	526.64	445.88	271.88	61.47	4.22	0.00	0.00	0.00	0.00	0.78	102.00	380.57	**64.98**
1.00m	534.61	453.74	276.26	64.73	4.35	0.00	0.00	0.00	0.00	0.94	106.53	388.50	**66.29**
1.25m	538.86	457.53	283.18	66.55	4.44	0.00	0.00	0.00	0.00	1.03	108.91	392.79	**67.15**
1.50m	543.36	462.05	287.53	68.59	4.53	0.00	0.00	0.00	0.00	1.15	111.56	397.21	**67.97**

Table A9. Conventional DF Cooling Thermal Loads per Square Meters Yearly.

A9. Conventional DF Cooling (Thermal Loads) (kWh)													SUM / square metres yearly (kWh/m^2y)
Cavity Length (m)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
NO BALCONY	-0.26	0.00	-0.10	-1.37	-44.26	-211.86	-502.73	-528.29	-254.14	-118.44	-9.90	0.00	**-60.56**
0.25m	0.00	0.00	0.00	-0.10	-33.62	-187.90	-464.39	-468.61	162.56	-25.74	0.00	0.00	**-48.66**
0.50m	0.00	0.00	0.00	-0.02	-31.34	-181.42	456.66	-458.42	-151.18	-21.25	0.00	0.00	**-47.11**
0.75m	0.00	0.00	0.00	0.00	-29.51	-176.31	-449.69	-450.55	-143.38	-18.30	0.00	0.00	**-45.93**
1.00m	0.00	0.00	0.00	0.00	-27.93	-171.67	-443.62	-443.18	-136.42	-15.84	0.00	0.00	**-44.88**
1.25m	0.00	0.00	0.00	0.00	-27.31	-169.40	-440.11	-439.05	-132.75	-14.77	0.00	0.00	**-44.33**
1.50m	0.00	0.00	0.00	0.00	-26.51	-166.73	-436.23	-434.57	-128.83	-13.50	0.00	0.00	**-43.71**

Table A10. Conventional DF Thermal Loads.

A10. Conventional DF Thermal Loads (kWh)													Yearly kWh
Cavity Depth (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
NO BALCONY	413.21	327.20	185.12	36.56	-41.15	-211.86	-502.73	-528.29	-254.14	-118.44	44.29	271.43	**-378.80**
0.25m	505.19	424.79	252.80	53.70	-29.73	-187.90	-464.39	-468.61	-162.56	-25.32	90.98	359.81	**348.76**
0.50m	517.79	437.14	263.75	58.03	-27.27	-181.42	-456.66	-458.42	-151.18	-20.63	97.20	372.06	**450.39**
0.75m	526.64	445.88	271.88	61.47	-25.29	-176.31	-449.69	-450.55	-143.38	-17.52	102.00	380.57	**525.70**
1.00m	534.61	453.74	276.26	64.73	-23.58	-171.67	-443.62	-443.18	-136.42	-14.90	106.53	388.50	**591.00**
1.25m	538.86	457.53	283.18	66.55	-22.87	-169.40	-440.11	-439.05	-132.75	-13.74	108.91	392.79	**629.90**
1.50m	543.36	462.05	287.53	68.59	-21.98	-166.73	-436.23	-434.57	-128.83	-12.35	111.56	397.21	**669.61**

Tables A11-A16. BIPV DF System Cavity Depth 0.25 m – 1.50 m Thermal Loads.

A11. DF BIPV DF Depth 0.25m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**516.39**	**436.40**	**264.53**	**59.24**	**4.12**	**0.00**	**0.00**	**0.00**	**0.00**	**0.63**	**97.25**	**370.88**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**-0.01**	**-30.07**	**-177.96**	**-450.99**	**-452.70**	**-149.01**	**-21.05**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A12. DF BIPV DF Depth 0.50m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**527.17**	**446.91**	**273.77**	**62.98**	**4.28**	**0.00**	**0.00**	**0.00**	**0.00**	**0.83**	**102.84**	**381.55**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-28.33**	**-172.92**	**-444.68**	**-445.08**	**-140.44**	**-17.64**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A13. DF BIPV Veranda Depth 0.75m THERMAL LOADS													
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**535.01**	**454.44**	**280.74**	**65.95**	**4.41**	**0.00**	**0.00**	**0.00**	**0.00**	**0.99**	**107.14**	**388.99**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-27.11**	**-168.94**	**-439.06**	**-438.30**	**-134.20**	**-15.37**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A14. DF BIPV Veranda Depth 1.00m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**542.13**	**461.46**	**287.27**	**68.85**	**4.53**	**0.00**	**0.00**	**0.00**	**0.00**	**1.15**	**111.33**	**395.80**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-25.92**	**-165.20**	**-433.93**	**-432.23**	**-128.05**	**-13.51**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A15. DF BIPV Veranda Depth 1.25m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**545.76**	**464.56**	**290.41**	**70.32**	**4.60**	**0.00**	**0.00**	**0.00**	**0.00**	**1.25**	**113.24**	**399.36**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-25.52**	**-163.69**	**-431.66**	**-429.55**	**-125.45**	**-12.67**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A16. DF BIPV Veranda Depth 1.50m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	**549.84**	**468.60**	**294.31**	**72.14**	**4.68**	**0.00**	**0.00**	**0.00**	**0.00**	**1.37**	**115.77**	**403.47**
Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**-24.90**	**-161.39**	**-428.51**	**-425.72**	**-122.00**	**-11.70**	**0.00**	**0.00**
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

Table A17. BIPV DF Heating Thermal Loads per Square Meters Yearly.

A17. BIPV Heating (THERMAL LOADS) (kWh)													SUM / square metres yearly (kWh/m²y)
Cavity Length (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
NO BALCONY	413.47	327.20	185.22	37.93	3.11	0.00	0.00	0.00	0.00	0.00	54.19	271.43	**46.83**
0.25m	516.39	436.40	264.53	59.24	4.12	0.00	0.00	0.00	0.00	0.63	97.25	370.88	**63.39**
0.50m	527.17	446.91	273.77	62.98	4.28	0.00	0.00	0.00	0.00	0.83	102.84	381.55	**65.23**
0.75m	535.01	454.44	280.74	65.95	4.41	0.00	0.00	0.00	0.00	0.99	107.14	388.99	**66.58**
1.00m	542.13	461.46	287.27	68.85	4.53	0.00	0.00	0.00	0.00	1.15	111.33	395.80	**67.84**
1.25m	545.76	464.56	290.41	70.32	4.60	0.00	0.00	0.00	0.00	1.25	113.24	399.36	**68.46**
1.50m	549.84	468.60	294.31	72.14	4.68	0.00	0.00	0.00	0.00	1.37	115.77	403.47	**69.21**

Table A18. BIPV DF Cooling Thermal Loads per Square Meters Yearly.

A18. BIPV Cooling (THERMAL LOADS) (kWh)													SUM / square metres yearly (kWh/m²y)
Cavity Length (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
NO BALCONY	-0.26	0.00	-0.10	-1.37	-44.26	-211.86	-502.73	-528.29	-254.14	-118.44	-9.90	0.00	**-60.56**
0.25m	0.00	0.00	0.00	-0.01	-30.07	-177.96	-450.99	-452.70	-149.01	-21.05	0.00	0.00	**-46.44**
0.50m	0.00	0.00	0.00	0.00	-28.33	-172.92	-444.68	-445.08	-140.44	-17.64	0.00	0.00	**-45.26**
0.75m	0.00	0.00	0.00	0.00	-27.11	-168.94	-439.06	-438.30	-134.20	-15.37	0.00	0.00	**-44.31**
1.00m	0.00	0.00	0.00	0.00	-25.92	-165.20	-433.93	-432.23	-128.05	-13.51	0.00	0.00	**-43.44**
1.25m	0.00	0.00	0.00	0.00	-25.52	-163.69	-431.66	-429.55	-125.45	-12.67	0.00	0.00	**-43.06**
1.50m	0.00	0.00	0.00	0.00	-24.90	-161.39	-428.51	-425.72	-122.00	-11.70	0.00	0.00	**-42.54**

Table A19. BIPV DF Overall Thermal Loads.

A19. BIPV THERMAL LOADS (kWh)													Yearly kWh
Cavity Depth (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
NO BALCONY	413.21	327.20	185.12	36.56	-41.15	-211.86	-502.73	-528.29	-254.14	-118.44	44.29	271.43	**-378.80**
0.25m	516.39	436.40	264.53	59.23	-25.95	-177.96	-450.99	-452.70	-149.01	-20.42	97.25	370.88	**467.65**
0.50m	527.17	446.91	273.77	62.98	-24.05	-172.92	-444.68	-445.08	-140.44	-16.81	102.84	381.55	**551.24**
0.75m	535.01	454.44	280.74	65.95	-22.70	-168.94	-439.06	-438.30	-134.20	-14.38	107.14	388.99	**614.69**
1.00m	542.13	461.46	287.27	68.85	-21.39	-165.20	-433.93	-432.23	-128.05	-12.36	111.33	395.80	**673.68**
1.25m	545.76	464.56	290.41	70.32	-20.92	-163.69	-431.66	-429.55	-125.45	-11.42	113.24	399.36	**700.96**
1.50m	549.84	468.60	294.31	72.14	-20.22	-161.39	-428.51	-425.72	-122.00	-10.33	115.77	403.47	**735.96**

Tables A20-A25. BIPV/T DF System Cavity Depth 0.25 m – 1.50 m Thermal Loads.

A20. DF BIPVT DF Depth 0.25m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	540.36	460.42	287.25	69.68	4.58	0.00	0.00	0.00	0.00	1.08	111.17	394.81
Cooling	kWh	0.00	0.00	0.00	0.00	-24.45	-159.98	-427.28	-428.31	-127.09	-13.42	0.00	0.00
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A21. DF BIPVT DF Depth 0.50m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	548.25	467.73	293.92	72.59	4.70	0.00	0.00	0.00	0.00	1.32	115.60	402.35
Cooling	kWh	0.00	0.00	0.00	0.00	-23.56	-157.02	-423.19	-422.70	-121.38	-11.61	0.00	0.00
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A22. DF BIPVT Veranda Depth 0.75m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	553.96	473.29	299.01	74.84	4.80	0.00	0.00	0.00	0.00	1.52	119.09	407.87
Cooling	kWh	0.00	0.00	0.00	0.00	-22.97	-154.99	-419.15	-418.15	-117.11	-10.38	0.00	0.00
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A23. DF BIPVT Veranda Depth 1.00m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	557.73	477.27	302.52	76.40	4.82	0.00	0.00	0.00	0.00	1.65	121.64	412.32
Cooling	kWh	0.00	0.00	0.00	0.00	-21.73	-151.90	-415.60	-412.37	-111.13	-8.60	0.00	0.00
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A24. DF BIPVT Veranda Depth 1.25m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	561.88	480.65	305.66	77.84	4.93	0.00	0.00	0.00	0.00	1.83	123.80	415.54
Cooling	kWh	0.00	0.00	0.00	0.00	-22.14	-152.35	-416.05	-412.57	-111.76	-8.86	0.00	0.00
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

A25. DF BIPVT Veranda Depth 1.50m THERMAL LOADS													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Lighting	kWh	17.79	16.07	17.79	17.22	17.79	17.22	17.79	17.79	17.22	17.79	17.22	17.79
Heating	kWh	564.53	483.53	308.16	79.05	4.98	0.00	0.00	0.00	0.00	1.97	125.59	418.40
Cooling	kWh	0.00	0.00	0.00	0.00	-21.86	-151.43	-414.58	-410.37	-109.69	-8.31	0.00	0.00
DHW	kWh	310.94	280.85	310.94	300.91	310.94	300.91	310.94	310.94	300.91	310.94	300.91	310.94

Table A26. BIPVT DF Heating Thermal Loads per Square Meters Yearly.

A26. BIPVT Heating THERMAL LOADS (kWh)													SUM / square metres yearly (kWh/m²y)
Cavity Depth (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
NO BALCONY	413.47	327.20	185.22	37.93	3.11	0.00	0.00	0.00	0.00	0.00	54.19	271.43	**46.83**
0.25m	540.36	460.42	287.25	69.68	4.58	0.00	0.00	0.00	0.00	1.08	111.17	394.81	**67.73**
0.50m	548.25	467.73	293.92	72.59	4.70	0.00	0.00	0.00	0.00	1.32	115.60	402.35	**69.07**
0.75m	553.96	473.29	299.01	74.84	4.80	0.00	0.00	0.00	0.00	1.52	119.09	407.87	**70.09**
1.00m	557.73	477.27	302.52	76.40	4.82	0.00	0.00	0.00	0.00	1.65	121.64	412.32	**70.81**
1.25m	561.88	480.65	305.66	77.84	4.93	0.00	0.00	0.00	0.00	1.83	123.80	415.54	**71.45**
1.50m	564.53	483.53	308.16	79.05	4.98	0.00	0.00	0.00	0.00	1.97	125.59	418.40	**71.96**

Table A27. BIPVT DF Cooling Thermal Loads per Square Meters Yearly.

A27. BIPVT Cooling THERMAL LOADS (kWh)													SUM / square metres yearly (kWh/m²y)
Cavity Depth (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
NO BALCONY	-0.26	0.00	-0.10	-1.37	-44.26	-211.86	-502.73	-528.29	-254.14	-118.44	-9.90	0.00	**-60.56**
0.25m	0.00	0.00	0.00	0.00	-24.45	-159.98	-427.28	-428.31	-127.09	-13.42	0.00	0.00	**-42.77**
0.50m	0.00	0.00	0.00	0.00	-23.56	-157.02	-423.19	-422.70	-121.38	-11.61	0.00	0.00	**-42.01**
0.75m	0.00	0.00	0.00	0.00	-22.97	-154.99	-419.15	-418.15	-117.11	-10.38	0.00	0.00	**-41.40**
1.00m	0.00	0.00	0.00	0.00	-21.73	-151.90	-415.60	-412.37	-111.13	-8.60	0.00	0.00	**-40.63**
1.25m	0.00	0.00	0.00	0.00	-22.14	-152.35	-416.05	-412.57	-111.76	-8.86	0.00	0.00	**-40.71**
1.50m	0.00	0.00	0.00	0.00	-21.86	-151.43	-414.58	-410.37	-109.69	-8.31	0.00	0.00	**-40.44**

Table A28. BIPVT DF Thermal Loads.

A28. BIPV/T THERMAL LOADS (kWh)													Yearly kWh
Cavity Depth (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	
NO BALCONY	413.21	327.20	185.12	36.56	-41.15	-211.86	-502.73	-528.29	-254.14	-118.44	44.29	271.43	**-378.80**
0.25m	540.36	460.42	287.25	69.68	-19.87	-159.98	-427.28	-428.31	-127.09	-12.34	111.17	394.81	**688.82**
0.50m	548.25	467.73	293.92	72.59	-18.86	-157.02	-423.19	-422.70	-121.38	-10.29	115.60	402.35	**747.00**
0.75m	553.96	473.29	299.01	74.84	-18.17	-154.99	-419.15	-418.15	-117.11	-8.86	119.09	407.87	**791.63**
1.00m	557.73	477.27	302.52	76.40	-16.91	-151.90	-415.60	-412.37	-111.13	-6.95	121.64	412.32	**833.02**
1.25m	561.88	480.65	305.66	77.84	-17.21	-152.35	-416.05	-412.57	-111.76	-7.03	123.80	415.54	**848.40**
1.50m	564.53	483.53	308.16	79.05	-16.88	-151.43	-414.58	-410.37	-109.69	-6.34	125.59	418.40	**869.97**

10.2 Primary Energy Results

Table A29. Base Model No Balcony Primary Energy Needs (PE).

A29. BASE MODEL NO BALCONY PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	137.82	109.07	62.27	12.81	1.04	0.00	0.00	0.00	0.00	0.00	18.31	91.20
Cooling	kWh	0.08	0.00	0.02	0.38	13.33	61.16	142.32	148.47	73.50	34.59	2.65	0.00
PRIMARY ENERGY Heating	kWh	**372.11**	**294.49**	**168.13**	**34.59**	**2.81**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**49.44**	**246.24**
PRIMARY ENERGY Cooling	kWh	**0.22**	**0.00**	**0.05**	**1.03**	**35.99**	**165.13**	**384.26**	**400.87**	**198.45**	**93.39**	**7.16**	**0.00**
PRIMARY ENERGY SUM	kWh	**372.33**	**294.49**	**168.18**	**35.61**	**38.80**	**165.13**	**384.26**	**400.87**	**198.45**	**93.39**	**56.59**	**246.24**

Tables A30 -A35. Conventional DF System Cavity Depth 0.25 m – 1.50 m Primary Energy Needs (PE).

A30. DF CONVENTIONAL DF Depth 0.25m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	168.40	141.60	84.27	17.94	1.30	0.00	0.00	0.00	0.00	0.14	30.33	119.94
Cooling	kWh	0.00	0.00	0.00	0.10	0.03	53.69	132.68	133.88	46.45	7.35	0.00	0.00
PRIMARY ENERGY Heating	kWh	454.68	382.32	227.53	48.44	3.51	0.00	0.00	0.00	0.00	0.38	81.89	323.84
PRIMARY ENERGY Cooling	kWh	0.00	0.00	0.00	0.27	0.08	144.96	358.24	361.48	125.42	19.85	0.00	0.00
PRIMARY ENERGY SUM	kWh	454.68	382.32	227.53	48.71	3.59	144.96	358.24	361.48	125.42	20.22	81.89	323.84

A31. DF CONVENTIONAL DF Depth 0.50m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	172.60	145.71	87.96	19.36	1.36	0.00	0.00	0.00	0.00	0.21	32.42	124.02
Cooling	kWh	0.00	0.00	0.00	0.01	8.95	51.83	130.50	130.98	43.18	6.06	0.00	0.00
PRIMARY ENERGY Heating	kWh	466.02	393.42	237.49	52.27	3.67	0.00	0.00	0.00	0.00	0.57	87.53	334.85
PRIMARY ENERGY Cooling	kWh	0.00	0.00	0.00	0.03	24.17	139.94	352.35	353.65	116.59	16.36	0.00	0.00
PRIMARY ENERGY SUM	kWh	466.02	393.42	237.49	52.30	27.84	139.94	352.35	353.65	116.59	16.93	87.53	334.85

A32. DF CONVENTIONAL Veranda Depth 0.75m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	175.54	148.63	90.67	20.51	1.41	0.00	0.00	0.00	0.00	0.26	34.03	126.86
Cooling	kWh	0.00	0.00	0.00	0.00	9.08	51.19	127.68	127.23	42.35	5.73	0.00	0.00
PRIMARY ENERGY Heating	kWh	473.96	401.30	244.81	55.38	3.81	0.00	0.00	0.00	0.00	0.70	91.88	342.52
PRIMARY ENERGY Cooling	kWh	0.00	0.00	0.00	0.00	24.52	138.21	344.74	343.52	114.35	15.47	0.00	0.00
PRIMARY ENERGY SUM	kWh	473.96	401.30	244.81	55.38	28.32	138.21	344.74	343.52	114.35	16.17	91.88	342.52

A33. DF CONVENTIONAL Veranda Depth 1.00m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	178.20	151.25	93.13	21.60	1.45	0.00	0.00	0.00	0.00	0.31	35.54	129.50
Cooling	kWh	0.00	0.00	0.00	0.00	8.61	49.85	125.96	125.19	40.31	4.97	0.00	0.00
PRIMARY ENERGY Heating	kWh	481.14	408.38	251.45	58.32	3.92	0.00	0.00	0.00	0.00	0.84	95.96	349.65
PRIMARY ENERGY Cooling	kWh	0.00	0.00	0.00	0.00	23.25	134.60	340.09	338.01	108.84	13.42	0.00	0.00
PRIMARY ENERGY SUM	kWh	481.14	408.38	251.45	58.32	27.16	134.60	340.09	338.01	108.84	14.26	95.96	349.65

A34. DF CONVENTIONAL Veranda Depth 1.25m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	179.62	152.51	94.44	22.20	1.48	0.00	0.00	0.00	0.00	0.35	36.34	130.93
Cooling	kWh	0.00	0.00	0.00	0.00	8.43	49.21	124.98	124.08	39.29	4.64	0.00	0.00
PRIMARY ENERGY Heating	kWh	484.97	411.78	254.99	59.94	4.00	0.00	0.00	0.00	0.00	0.95	98.12	353.51
PRIMARY ENERGY Cooling	kWh	0.00	0.00	0.00	0.00	22.76	132.87	337.45	335.02	106.08	12.53	0.00	0.00
PRIMARY ENERGY SUM	kWh	484.97	411.78	254.99	59.94	26.76	132.87	337.45	335.02	106.08	13.47	98.12	353.51

A35. DF CONVENTIONAL Veranda Depth 1.50m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	181.12	154.02	95.88	22.88	1.51	0.00	0.00	0.00	0.00	0.38	37.22	132.41
Cooling	kWh	0.00	0.00	0.00	0.00	8.19	48.44	123.91	122.84	38.11	4.25	0.00	0.00
PRIMARY ENERGY Heating	kWh	489.02	415.85	258.88	61.78	4.08	0.00	0.00	0.00	0.00	1.03	100.49	357.51
PRIMARY ENERGY Cooling	kWh	0.00	0.00	0.00	0.00	22.11	130.79	334.56	331.67	102.90	11.48	0.00	0.00
PRIMARY ENERGY SUM	kWh	489.02	415.85	258.88	61.78	26.19	130.79	334.56	331.67	102.90	12.50	100.49	357.51

Table A36. Conventional DF Primary Energy Needs.

A36. Conventional DF PRIMARY ENERGY (kWh)													Yearly (kWh)	SUM / square metres yearly (kWh/m²y)
Cavity Length (m)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**		
NO BALCONY	372.33	294.49	168.18	35.61	38.80	165.13	384.26	400.87	198.45	93.39	56.59	246.24	**2454.35**	**88.93**
0.25m	454.68	382.32	227.53	48.71	3.59	144.96	358.24	361.48	125.42	20.22	81.89	323.84	**2532.87**	**91.77**
0.50m	466.02	393.42	237.49	52.30	27.84	139.94	352.35	353.65	116.59	16.93	87.53	334.85	**2578.91**	**93.44**
0.75m	473.96	401.30	244.81	55.38	28.32	138.21	344.74	343.52	114.35	16.17	91.88	342.52	**2595.16**	**94.03**
1.00m	481.14	408.38	251.45	58.32	27.16	134.60	340.09	338.01	108.84	14.26	95.96	349.65	**2607.85**	**94.49**
1.25m	484.97	411.78	254.99	59.94	26.76	132.87	337.45	335.02	106.08	13.47	98.12	353.51	**2614.95**	**94.74**
1.50m	489.02	415.85	258.88	61.78	26.19	130.79	334.56	331.67	102.90	12.50	100.49	357.51	**2622.13**	**95.00**

Tables A37-A42. BIPV DF System Cavity Depth 0.25 m – 1.50 m Primary Energy Needs (PE).

A37. DF BIPV DF Depth 0.25m PRIMARY ENERGY													
		Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Heating	kWh	172.13	145.47	88.18	19.75	1.37	0.00	0.00	0.00	0.00	0.21	32.42	123.63
Cooling	kWh	0.00	0.00	0.00	0.00	9.23	51.67	128.04	127.84	43.97	6.56	0.00	0.00
PRIMARY ENERGY Heating	kWh	**464.75**	**392.77**	**238.09**	**53.33**	**3.70**	**0.00**	**0.00**	**0.00**	**0.00**	**0.57**	**87.53**	**333.80**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**24.92**	**139.51**	**345.71**	**345.17**	**118.72**	**17.71**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**464.75**	**392.77**	**238.09**	**53.33**	**28.62**	**139.51**	**345.71**	**345.17**	**118.72**	**18.28**	**87.53**	**333.80**
Energy Production BIPVs	kWh	105.84	102.53	108.05	108.05	97.57	84.89	92.06	110.25	131.20	138.36	118.52	109.15
PE_Energy Production BIPVs	kWh	**285.77**	**276.84**	**291.72**	**291.72**	**263.44**	**229.21**	**248.56**	**297.68**	**354.23**	**373.58**	**320.00**	**294.70**

A38. DF BIPV DF Depth 0.50m PRIMARY ENERGY													
		Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Heating	kWh	175.72	148.97	91.29	21.00	1.43	0.00	0.00	0.00	0.00	0.28	34.31	127.19
Cooling	kWh	0.00	0.00	0.00	0.00	8.72	50.22	126.30	125.74	41.48	5.52	0.00	0.00
PRIMARY ENERGY Heating	kWh	**474.44**	**402.22**	**246.48**	**56.70**	**3.86**	**0.00**	**0.00**	**0.00**	**0.00**	**0.76**	**92.64**	**343.41**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**23.54**	**135.59**	**341.01**	**339.50**	**112.00**	**14.90**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**474.44**	**402.22**	**246.48**	**56.70**	**27.41**	**135.59**	**341.01**	**339.50**	**112.00**	**15.66**	**92.64**	**343.41**
Energy Production BIPVs	kWh	**105.84**	**102.53**	**108.05**	**108.05**	**97.57**	**84.89**	**92.06**	**110.25**	**131.20**	**138.36**	**118.52**	**109.15**
PE_Energy Production BIPVs	kWh	**285.77**	**276.84**	**291.72**	**291.72**	**263.44**	**229.21**	**248.56**	**297.68**	**354.23**	**373.58**	**320.00**	**294.70**

A39. DF BIPV Veranda Depth 0.75m PRIMARY ENERGY													
		Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Heating	kWh	178.34	151.48	93.62	22.00	1.47	0.00	0.00	0.00	0.00	0.33	35.74	129.67
Cooling	kWh	0.00	0.00	0.00	0.00	8.36	49.07	124.73	123.90	39.68	4.83	0.00	0.00
PRIMARY ENERGY Heating	kWh	**481.52**	**409.00**	**252.77**	**59.40**	**3.97**	**0.00**	**0.00**	**0.00**	**0.00**	**0.89**	**96.50**	**350.11**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**22.57**	**132.49**	**336.77**	**334.53**	**107.14**	**13.04**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**481.52**	**409.00**	**252.77**	**59.40**	**26.54**	**132.49**	**336.77**	**334.53**	**107.14**	**13.93**	**96.50**	**350.11**
Energy Production BIPVs	kWh	**105.84**	**102.53**	**108.05**	**108.05**	**97.57**	**84.89**	**92.06**	**110.25**	**131.20**	**138.36**	**118.52**	**109.15**
PE_Energy Production BIPVs	kWh	**285.77**	**276.84**	**291.72**	**291.72**	**263.44**	**229.21**	**248.56**	**297.68**	**354.23**	**373.58**	**320.00**	**294.70**

A40. DF BIPV Veranda Depth 1.00m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	180.71	153.82	95.79	22.97	1.51	0.00	0.00	0.00	0.00	0.39	37.14	131.94
Cooling	kWh	0.00	0.00	0.00	0.00	8.00	47.99	123.26	122.23	37.87	4.25	0.00	0.00
PRIMARY ENERGY Heating	kWh	**487.92**	**415.31**	**258.63**	**62.02**	**4.08**	**0.00**	**0.00**	**0.00**	**0.00**	**1.05**	**100.28**	**356.24**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**21.60**	**129.57**	**332.80**	**330.02**	**102.25**	**11.48**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**487.92**	**415.31**	**258.63**	**62.02**	**25.68**	**129.57**	**332.80**	**330.02**	**102.25**	**12.53**	**100.28**	**356.24**
Energy Production BIPVs	kWh	**105.84**	**102.53**	**108.05**	**108.05**	**97.57**	**84.89**	**92.06**	**110.25**	**131.20**	**138.36**	**118.52**	**109.15**
PE_Energy Production BIPVs	kWh	**285.77**	**276.84**	**291.72**	**291.72**	**263.44**	**229.21**	**248.56**	**297.68**	**354.23**	**373.58**	**320.00**	**294.70**

A41. DF BIPV Veranda Depth 1.25m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	181.92	154.85	96.84	23.46	1.53	0.00	0.00	0.00	0.00	0.42	37.78	133.12
Cooling	kWh	0.00	0.00	0.00	0.00	7.89	47.57	122.63	121.46	37.13	3.98	0.00	0.00
PRIMARY ENERGY Heating	kWh	**491.18**	**418.10**	**261.47**	**63.34**	**4.13**	**0.00**	**0.00**	**0.00**	**0.00**	**1.13**	**102.01**	**359.42**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**21.30**	**128.44**	**331.10**	**327.94**	**100.25**	**10.75**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**491.18**	**418.10**	**261.47**	**63.34**	**25.43**	**128.44**	**331.10**	**327.94**	**100.25**	**11.88**	**102.01**	**359.42**
Energy Production BIPVs	kWh	**105.84**	**102.53**	**108.05**	**108.05**	**97.57**	**84.89**	**92.06**	**110.25**	**131.20**	**138.36**	**118.52**	**109.15**
PE_Energy Production BIPVs	kWh	**285.77**	**276.84**	**291.72**	**291.72**	**263.44**	**229.21**	**248.56**	**297.68**	**354.23**	**373.58**	**320.00**	**294.70**

A42. DF BIPV Veranda Depth 1.50m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	183.28	156.20	98.13	24.06	1.56	0.00	0.00	0.00	0.00	0.46	38.62	134.49
Cooling	kWh	0.00	0.00	0.00	0.00	7.70	46.90	121.74	120.39	36.13	3.68	0.00	0.00
PRIMARY ENERGY Heating	kWh	**494.86**	**421.74**	**264.95**	**64.96**	**4.21**	**0.00**	**0.00**	**0.00**	**0.00**	**1.24**	**104.27**	**363.12**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**20.79**	**126.63**	**328.70**	**325.05**	**97.55**	**9.94**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**494.86**	**421.74**	**264.95**	**64.96**	**25.00**	**126.63**	**328.70**	**325.05**	**97.55**	**11.18**	**104.27**	**363.12**
Energy Production BIPVs	kWh	**105.84**	**102.53**	**108.05**	**108.05**	**97.57**	**84.89**	**92.06**	**110.25**	**131.20**	**138.36**	**118.52**	**109.15**
PE_Energy Production BIPVs	kWh	**285.77**	**276.84**	**291.72**	**291.72**	**263.44**	**229.21**	**248.56**	**297.68**	**354.23**	**373.58**	**320.00**	**294.70**

Table A43. BIPV DF Primary Energy Needs (PE).

A43. BIPV PRIMARY ENERGY WITH RES (kWh)													Yearly (kWh)	SUM / square metres yearly (kWh/m²y)
Cavity Length (m)	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec		
NO BALCONY	372.33	294.49	168.18	35.61	38.80	165.13	384.26	400.87	198.45	93.39	56.59	246.24	**2454.35**	**88.93**
0.25m	178.98	115.93	-53.64	-238.40	-234.82	-89.70	97.15	47.49	-235.51	-355.30	-232.47	39.10	**-961.18**	**-34.83**
0.50m	188.68	125.38	-45.24	-235.02	-236.04	-93.62	92.45	41.82	-242.24	-357.92	-227.36	48.71	**-940.39**	**-34.07**
0.75m	195.75	132.16	-38.95	-232.32	-236.90	-96.72	88.21	36.86	-247.10	-359.65	-223.50	55.41	**-926.75**	**-33.58**
1.00m	202.15	138.48	-33.09	-229.70	-237.77	-99.64	84.24	32.35	-251.98	-361.05	-219.72	61.54	**-914.20**	**-33.12**
1.25m	205.42	141.26	-30.25	-228.38	-238.01	-100.77	82.54	30.27	-253.98	-361.70	-217.99	64.73	**-906.88**	**-32.86**
1.50m	209.09	144.90	-26.77	-226.76	-238.44	-102.58	80.14	27.38	-256.68	-362.40	-215.73	68.42	**-899.43**	**-32.59**
PE_Energy Production BIPVs	**285.77**	**276.84**	**291.72**	**291.72**	**263.44**	**229.21**	**248.56**	**297.68**	**354.23**	**373.58**	**320.00**	**294.70**		

Tables A44-A49. BIPVT DF System Cavity Depth 0.25 m – 1.50 m Primary Energy Needs (PE).

A44. DF BIPVT DF Depth 0.25m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	180.12	153.47	95.75	23.23	1.53	0.00	0.00	0.00	0.00	0.36	37.06	131.60
Cooling	kWh	0.00	0.00	0.00	0.00	7.58	46.49	121.39	121.01	37.67	4.26	0.00	0.00
PRIMARY ENERGY Heating	kWh	**486.32**	**414.37**	**258.53**	**62.72**	**4.13**	**0.00**	**0.00**	**0.00**	**0.00**	**0.97**	**100.06**	**355.32**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**20.47**	**125.52**	**327.75**	**326.73**	**101.71**	**11.50**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**486.32**	**414.37**	**258.53**	**62.72**	**24.60**	**125.52**	**327.75**	**326.73**	**101.71**	**12.47**	**100.06**	**355.32**
Energy Production BIPVTs	kWh	126.00	122.06	128.63	128.63	116.16	101.06	109.59	131.25	156.19	164.72	141.09	129.94
PE_Energy Production BIPVTs	kWh	**340.20**	**329.57**	**347.29**	**347.29**	**313.62**	**272.87**	**295.90**	**354.38**	**421.71**	**444.74**	**380.95**	**350.83**

A45. DF BIPVT DF Depth 0.50m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	182.75	155.91	97.99	24.20	1.57	0.00	0.00	0.00	0.00	0.44	38.55	134.12
Cooling	kWh	0.00	0.00	0.00	0.00	7.30	45.63	120.26	119.48	35.98	3.67	0.00	0.00
PRIMARY ENERGY Heating	kWh	**493.43**	**420.96**	**264.57**	**65.34**	**4.24**	**0.00**	**0.00**	**0.00**	**0.00**	**1.19**	**104.09**	**362.12**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**19.71**	**123.20**	**324.70**	**322.60**	**97.15**	**9.91**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**493.43**	**420.96**	**264.57**	**65.34**	**23.95**	**123.20**	**324.70**	**322.60**	**97.15**	**11.10**	**104.09**	**362.12**
Energy Production BIPVTs	kWh	126.00	122.06	128.63	128.63	116.16	101.06	109.59	131.25	156.19	164.72	141.09	129.94
PE_Energy Production BIPVTs	kWh	**340.20**	**329.57**	**347.29**	**347.29**	**313.62**	**272.87**	**295.90**	**354.38**	**421.71**	**444.74**	**380.95**	**350.83**

A46. DF BIPVT Veranda Depth 0.75m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	184.65	157.76	99.68	24.95	1.60	0.00	0.00	0.00	0.00	0.51	39.71	135.96
Cooling	kWh	0.00	0.00	0.00	0.00	7.12	45.00	119.33	118.25	34.72	3.28	0.00	0.00
PRIMARY ENERGY Heating	kWh	**498.56**	**425.95**	**269.14**	**67.37**	**4.32**	**0.00**	**0.00**	**0.00**	**0.00**	**1.38**	**107.22**	**367.09**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**19.22**	**121.50**	**322.19**	**319.28**	**93.74**	**8.86**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**498.56**	**425.95**	**269.14**	**67.37**	**23.54**	**121.50**	**322.19**	**319.28**	**93.74**	**10.23**	**107.22**	**367.09**
Energy Production BIPVTs	kWh	126.00	122.06	128.63	128.63	116.16	101.06	109.59	131.25	156.19	164.72	141.09	129.94
PE_Energy Production BIPVTs	kWh	**340.20**	**329.57**	**347.29**	**347.29**	**313.62**	**272.87**	**295.90**	**354.38**	**421.71**	**444.74**	**380.95**	**350.83**

A47. DF BIPVT Veranda Depth 1.00m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	185.91	159.09	100.85	25.47	1.61	0.00	0.00	0.00	0.00	0.55	40.56	137.44
Cooling	kWh	0.00	0.00	0.00	0.00	6.77	44.19	118.20	116.69	33.00	2.74	0.00	0.00
PRIMARY ENERGY Heating	kWh	**501.96**	**429.54**	**272.30**	**68.77**	**4.35**	**0.00**	**0.00**	**0.00**	**0.00**	**1.49**	**109.51**	**371.09**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**18.28**	**119.31**	**319.14**	**315.06**	**89.10**	**7.40**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**501.96**	**429.54**	**272.30**	**68.77**	**22.63**	**119.31**	**319.14**	**315.06**	**89.10**	**8.88**	**109.51**	**371.09**
Energy Production BIPVTs	kWh	126.00	122.06	128.63	128.63	116.16	101.06	109.59	131.25	156.19	164.72	141.09	129.94
PE_Energy Production BIPVTs	kWh	**340.20**	**329.57**	**347.29**	**347.29**	**313.62**	**272.87**	**295.90**	**354.38**	**421.71**	**444.74**	**380.95**	**350.83**

A48. DF BIPVT Veranda Depth 1.25m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	187.30	160.22	101.90	25.96	1.64	0.00	0.00	0.00	0.00	0.61	41.29	138.52
Cooling	kWh	0.00	0.00	0.00	0.00	6.87	44.29	118.28	116.72	33.13	2.81	0.00	0.00
PRIMARY ENERGY Heating	kWh	**505.71**	**432.59**	**275.13**	**70.09**	**4.43**	**0.00**	**0.00**	**0.00**	**0.00**	**1.65**	**111.48**	**374.00**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**18.55**	**119.58**	**319.36**	**315.14**	**89.45**	**7.59**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**505.71**	**432.59**	**275.13**	**70.09**	**22.98**	**119.58**	**319.36**	**315.14**	**89.45**	**9.23**	**111.48**	**374.00**
Energy Production BIPVTs	kWh	126.00	122.06	128.63	128.63	116.16	101.06	109.59	131.25	156.19	164.72	141.09	129.94
PE_Energy Production BIPVTs	kWh	**340.20**	**329.57**	**347.29**	**347.29**	**313.62**	**272.87**	**295.90**	**354.38**	**421.71**	**444.74**	**380.95**	**350.83**

A49. DF BIPVT Veranda Depth 1.50m PRIMARY ENERGY													
		Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Heating	kWh	188.18	161.18	102.72	26.36	1.66	0.00	0.00	0.00	0.00	0.66	41.88	139.47
Cooling	kWh	0.00	0.00	0.00	0.00	6.79	44.01	117.83	116.12	32.54	2.64	0.00	0.00
PRIMARY ENERGY Heating	kWh	**508.09**	**435.19**	**277.34**	**71.17**	**4.48**	**0.00**	**0.00**	**0.00**	**0.00**	**1.78**	**113.08**	**376.57**
PRIMARY ENERGY Cooling	kWh	**0.00**	**0.00**	**0.00**	**0.00**	**18.33**	**118.83**	**318.14**	**313.52**	**87.86**	**7.13**	**0.00**	**0.00**
PRIMARY ENERGY SUM	kWh	**508.09**	**435.19**	**277.34**	**71.17**	**22.82**	**118.83**	**318.14**	**313.52**	**87.86**	**8.91**	**113.08**	**376.57**
Energy Production BIPVTs	kWh	126.00	122.06	128.63	128.63	116.16	101.06	109.59	131.25	156.19	164.72	141.09	129.94
PE_Energy Production BIPVTs	kWh	**340.20**	**329.57**	**347.29**	**347.29**	**313.62**	**272.87**	**295.90**	**354.38**	**421.71**	**444.74**	**380.95**	**350.83**

Table A50. BIPV/T DF Primary Energy Needs.

A50. BIPVT PRIMARY ENERGY WITH RES (kWh)													Yearly (kWh)	SUM / square metres yearly (kWh/m²y)
Cavity Length (m)	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**		
NO BALCONY	372.33	294.49	168.18	35.61	38.80	165.13	384.26	400.87	198.45	93.39	56.59	246.24	**2454.35**	**88.93**
0.25m	146.12	84.80	-88.76	-284.57	-289.02	-147.35	31.85	-27.65	-320.00	-432.27	-280.89	4.49	**-1603.24**	**-58.09**
0.50m	153.23	91.39	-82.71	-281.95	-289.67	-149.67	28.80	-31.78	-324.56	-433.64	-276.87	11.29	**-1586.15**	**-57.47**
0.75m	158.36	96.38	-78.15	-279.92	-290.08	-151.37	26.29	-35.10	-327.96	-434.51	-273.74	16.26	**-1573.54**	**-57.01**
1.00m	161.76	99.97	-74.99	-278.52	-291.00	-153.56	23.24	-39.31	-332.61	-435.86	-271.44	20.26	**-1572.05**	**-56.96**
1.25m	165.51	103.03	-72.16	-277.20	-290.64	-153.29	23.45	-39.23	-332.26	-435.51	-269.47	23.17	**-1554.59**	**-56.33**
1.50m	167.89	105.62	-69.94	-276.12	-290.81	-154.04	22.24	-40.85	-333.85	-435.83	-267.88	25.74	**-1547.84**	**-56.08**
PE_Energy Production BIPVTs	**285.77**	**276.84**	**291.72**	**291.72**	**263.44**	**229.21**	**248.56**	**297.68**	**354.23**	**373.58**	**320.00**	**294.70**		

10.3 Electric Energy Production Calculations BIPV and BIPV Systems

Table A51. BIPV Electricity Production PV-Sites.

A51. PV Sites Irradiance BIPV													
		Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Upper Part (1)	kWh/m²	96	92	100	99	88	77	84	100	118	126	107	99
Middle	kWh/m²	97	94	103	98	86	77	82	100	120	124	106	99
Lower Part (2)	kWh/m²	96	94	96	97	89	77	83	100	120	125	108	99
Mean Value (1&2)	kWh/m²	**96**	**93**	**98**	**98**	**88.5**	**77**	**83.5**	**100**	**119**	**125.5**	**107.5**	**99**
PV Panel	m²	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
Electricity Production	**kWh**	**105.84**	**102.53**	**108.05**	**108.05**	**97.57**	**84.89**	**92.06**	**110.25**	**131.20**	**138.36**	**118.52**	**109.15**

Table A52. BIPV/T Electricity Production PV-Sites.

A52. PV Sites Irradiance BIPVT													
		Jan	**Feb**	**Mar**	**Apr**	**May**	**June**	**July**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Upper Part (1)	kWh/m²	96	92	100	99	88	77	84	100	118	126	107	99
Middle	kWh/m²	97	94	103	98	86	77	82	100	120	124	106	99
Lower Part (2)	kWh/m²	96	94	96	97	89	77	83	100	120	125	108	99
Mean Value (1&2)	kWh/m²	**96**	**93**	**98**	**98**	**88.5**	**77**	**83.5**	**100**	**119**	**125.5**	**107.5**	**99**
PV Panel	m²	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25	5.25
Electricity Production	**kWh**	**126.00**	**122.06**	**128.63**	**128.63**	**116.16**	**101.06**	**109.59**	**131.25**	**156.19**	**164.72**	**141.09**	**129.94**

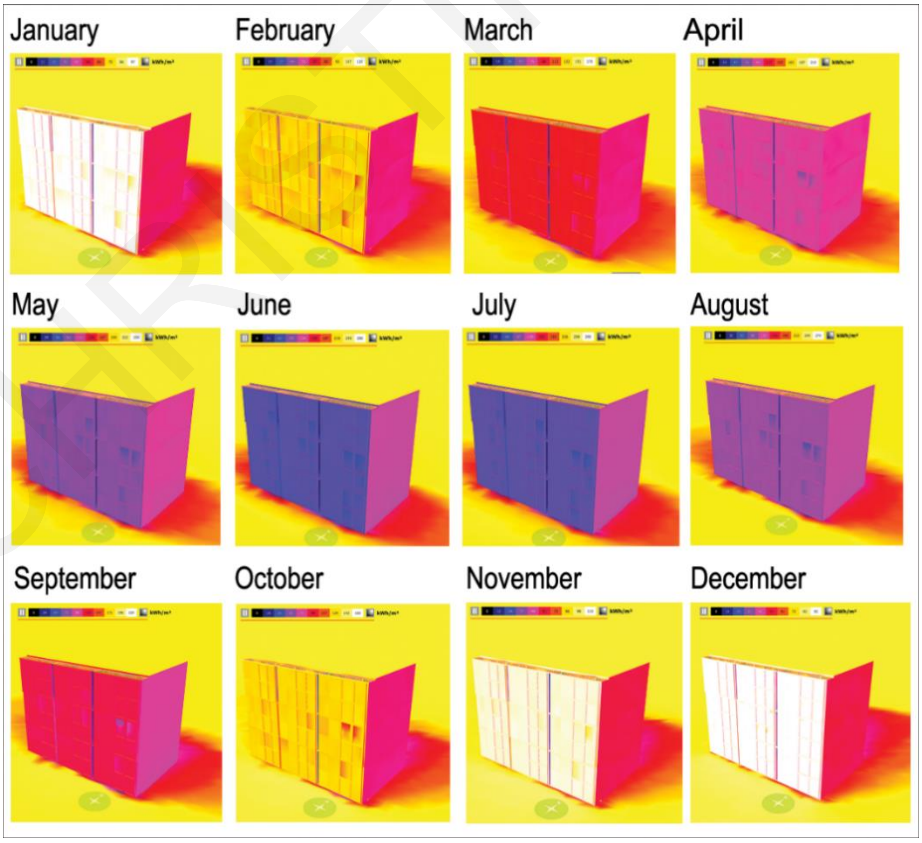


Figure A1. PV-Sites Model, Solar Radiation Levels South Elevation.

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