DEPARTMENT OF ELECTRICAL AND COMPUTER ENGINEERING

TECHNO-ECONOMIC ASSESSMENT OF ENERGY STORAGE SYSTEMS

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ΠΕΡΙΛΗΨΗ

Σε παγκόσμιο επίπεδο, το ενδιαφέρον για τα συστήματα αποθήκευσης ενέργειας αυξάνεται ως μία από τις κύριες τεχνολογίες που επιτρέπουν μια ουδέτερη για το κλίμα οικονομία. Αυτό το ενδιαφέρον, συγκεκριμένα για τα συστήματα αποθήκευσης ενέργειας μπαταρίας, δείχνει την απότομη πρόοδο στη μείωση του κόστους τους και στην αύξηση της απόδοσης τους.

Ο στόχος αυτής της εργασίας είναι να πραγματοποιηθεί μια ολοκληρωμένη έρευνα και μια λεπτομερή ανάλυση του κόστους και των πλεονεκτημάτων των συστημάτων αποθήκευσης ενέργειας για τη στήριξη της πορείας του συστήματος ισχύος της Κύπρου για το 2030. Προκειμένου να επιτευχθεί αυτός ο στόχος και να επιλεγούν κατάλληλες επιλογές αποθήκευσης ηλεκτρικής ενέργειας ειδικά για την περίπτωση του συστήματος ισχύος της Κύπρου, πραγματοποιήθηκε ένας κανόνας αναγνώρισης και μεθοδολογία κατάταξης. Ακολούθησε μια τεχνοοικονομική αξιολόγηση των επιλεγμένων λύσεων αποθήκευσης, η οποία εξετάζει τις επιλογές κατανεμημένης αποθήκευσης μικρής κλίμακας που θα εγκατασταθούν πίσω από το μετρητή. Ο χώρος αποθήκευσης πίσω από τον μετρητή βρίσκεται στην πλευρά του καταναλωτή/παραγωγού και σκοπός του είναι να αυξήσει την αυτοκατανάλωση από ενέργεια που προέρχεται από ΑΠΕ και παράγεται τοπικά και ταυτόχρονα να μειώσει το συνολικό κόστος της εισαγόμενης ηλεκτρικής ενέργειας.

Η μελέτη αυτής της εργασίας αρχικά κάνει μια επισκόπηση των τεχνολογιών αποθήκευσης ηλεκτρικής ενέργειας που είναι διαθέσιμες στην αγορά και έχουν δοκιμαστεί σε εργαστήρια. Στη συνέχεια, προσδιορίζονται οι βασικοί δείκτες απόδοσης σχετικά με τεχνικούς, εμπορικούς και περιβαλλοντικούς παράγοντες. Αυτοί οι δείκτες σχετίζονται με την απόδοση προεπιλεγμένων συστημάτων αποθήκευσης μικρής κλίμακας ή κλίμακας δικτύου που είναι κατάλληλα για την περίπτωση του συστήματος ισχύος της Κύπρου. Στη συνέχεια, πραγματοποιείται χαρτογράφηση σε γενικό επίπεδο μεταξύ των διαθέσιμων τεχνολογιών αποθήκευσης ηλεκτρικής ενέργειας και των υπηρεσιών που είναι σε θέση να παρέχουν.

Σε αυτήν την εργασία, προκειμένου να αξιολογηθεί η περίπτωση του κατανεμημένου χώρου αποθήκευσης μικρής κλίμακας πίσω από τον μετρητή, χρησιμοποιείται η προσέγγιση Net-Present-Value (NPV). Επιπλέον, το σύστημα αποθήκευσης ενέργειας έχει διάφορα οφέλη όπως η μείωση της συνολικής ετήσιας κατανάλωσης ηλεκτρικής ενέργειας από το

δίκτυο, τη μείωση του κόστους της ηλεκτρικής ενέργειας για τους καταναλωτές και την αύξηση του μεριδίου ΑΠΕ στην παραγωγή ηλεκτρικής ενέργειας.

ABSTRACT

Globally the interest on energy storage systems (ESSs) is increasing as one of the main technologies that enable towards a climate neutral economy. This interest, specific for the battery energy storage systems (BESSs), is showing on the sharp progress in lowering their costs and increasing their performance.

The aim of this work is to do a comprehensive survey and an in-detail analysis of the costs and benefits of ESSs to support the 2030's roadmap of the Power System of Cyprus (PSoC). In order to reach this target and to select suitable options of electricity storage specific for the case of the PSoC, an identification rule and ranking methodology took place. A techno-economic assessment of the selected storage solutions is following, which examines the options of distributed small-scale storage to be installed behind-the-meter (BTM). The BTM storage is located at the side of the consumer/prosumer and its aim is to increase the self-consumption from locally produced RES energy and at the same time to reduce the total cost of imported electricity.

The study of this work initially makes an overview of the electricity storage technologies which are available in the market and have been tested in laboratories. Then, the key performance indicators regarding technical, commercial and environmental factors are identified. These indicators are related with the performance of both small and grid scale storage systems which are suitable for the case of the PSoC. Subsequently, is carried out a mapping at general level between the available electricity storage technologies and the services that they are able to provide.

In this work, in order to evaluate the case of distributed BTM small-scale storage, the approach of Net-Present-Value (NPV) is applied. Moreover, the ESSs have various benefits such as the reduction in the total annual consumption of electricity from the grid, the reduction of the levelized cost of electricity for the consumers and the RES share in the electricity production is increased.

I dedicate this thesis to the memory of Prof. Elias Kyriakides for all his guidance

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BESS	Battery Energy Storage System
BTM	Behind the Meter
CAES	Compressed Air Energy Storage
CAPEX	Capital Expenditure
CERA	Cyprus Energy Regulatory Authority
DoD	Depth of Discharge
EAC	Electricity Authority of Cyprus
ESS	Energy Storage System
FESS	Flywheel Energy Storage System
FRR	Frequency Restoration Reserve
HV	High Voltage
IPP	Independent Power Producer
IRENA	International Renewable Agency
LFP	Lithium Ferro Phosphate
LTO	Lithium Titanate
LV	Low Voltage
MESS	Mechanical Energy Storage System
MV	Medium Voltage
NaNiCl	Sodium Nickel Chloride
NaS	Sodium Sulphur
NCA	Nickel Cobalt Aluminium
NMC	Nickel Manganese Cobalt
NPV	Net present value
PCS	Power Conversion System
PHS	Pumped Hydro Storage
PV	Photovoltaics
RES	Renewable Energy Sources
T&D	Transmission and Distribution
VRB	Vanadium Redox Battery
VRLA	Valve-Regulated Lead Acid
WF	Wind Farm
ZBB	Zinc Bromine Battery
ΔP	Power variation

CHAPTER 1

INTRODUCTION

Renewable energy sources (RESs) currently correspond to a significant share of the energy mix and affect the quality or reliability of a power system. Worldwide, the countries in order to achieve goals regarding the emission reduction, energy independence and improved reliability of the infrastructure, try to increase the RES penetration into utility grids. However, in the case of high share of RES penetration into the power system, negative effects will take place on the whole grid.

Nowadays, the RESs which are integrated with energy storage systems (ESSs) constitute one of the most reliable solutions in order to facilitate the increased penetration of distributed RES. These technologies are able for dispatching and added benefits will be provided to utilities, owners and customers under their great reliability, improved quality of the power and reduced energy costs.

1.1 Motivation and Objectives

The installation of storage technologies, according to a recent report (March 2020) of the International Renewable Energy Agency (IRENA) [1], is the most significant potential and viable economic option for islands and in remote areas because of their high electricity prices, or to support the growth of the renewable energy, for consumer/prosumer in countries where the share of rooftop solar PV is high and for transmission and distribution grids of countries which have power system with limited flexibility and are transferring to power system which will be based on RESs.

The electricity price in Cyprus is one of the highest average electricity price in Europe [2]. Although, the installed capacity of RES power is increasing, the PSoC has a large dependence on the imported fossil fuels and electricity which is produced by conventional thermal power plants [3]. The electricity price could be reduced by using energy storage technologies.

The PSoC has a great renewable energy potential, mainly for expansion of photovoltaics (PV), due to the high solar irradiation potential of the island. However, in a scenario with large penetration of energy from solar, the power that generated from the PV units may surpass the load demand during the noon, when the PV production is high and the load demand is low. Thus, the excess energy will be curtailed unless a storage unit will be installed to absorbed it.

Moreover, the targets of RES penetration of Cyprus for the year 2030 is 26%, while the penetration for the year 2020 was 11.7%. In order to increase this penetration in the following years and allow the country to reach its goals of RES and enable the intense of penetration of RES towards to a sustainable development for future power systems the contribution of the ESSs is very important.

The use of battery energy storage systems (BESSs) in electricity grids worldwide is currently increasing and is expected to exponentially increase in the near future since the cost of BESSs is reduced. The BESSs are mainly used in grids dependent on fuel oil imports and with high share of variable RESs [4]. Variability and uncertainty of variable RESs, such as from wind power farms (WFs) and PVs, are added on the uncertainty of load demand and of the availability of conventional power units [5] and as a result more spinning reserve is necessary and for the operation of the system more flexibility is needed. In order to address challenges that come from variable RESs, the energy storages are able to supply a variety of services. Moreover, the BESS in low-voltage side of the grid could reduce the interaction of consumer with the grid, reduce grid energy losses, reduce the reverse power flow that can cause congestion problems, and reduce the power injection during noon hours that cannot always absorbed by the system and may lead to curtailments

In consideration of the above key challenges/issues important for the PSoC, the main general objectives of this M.Sc. dissertation can be summarized as follows:

- Reduce the cost of electricity by integrating energy storage technologies
- Increase the allowable RES penetration limit of a power system by exploiting the flexibilities of energy storage systems
- Respond to operational challenges for the power systems which are related to the variable RESs nature, through services provided by energy storage systems

1.2 Contribution

This work applies a techno-economic analysis which has the ability to identify the most suitable storage technologies for the PSoC in order to increase the RES penetration in the next years and allow the Cyprus to reach its national targets of climate and energy. This thesis includes a comprehensive overview of storage technologies considering for the technical, economic and environmental parameters of each technology, along with their suitability for the certain case of islanded PSoC. The analysis includes the process for identifying the key performance indicators (KPIs) and the methodology for ranking of the storage technologies according to a set of smart grid application services that are most suitable to provide at grid level (upstream the meter) or towards the end-user (behind the meter). The methodology that is followed in order to produce this thesis is based on the Framework for Electricity Storage Valuation (FESV) recently proposed by IRENA [1], which is one of the most recent international guidelines for carrying out a techno-economic analysis for ESSs, specifically adapted for the case of Cyprus.

Moreover, an economic assessment was performed to evaluate if the investment for the installation of the most suitable type of ESS at low voltage side (BTM storage investments) will be profitable. The aim of this investment is to increase the self-consumption from on-site produced energy and at the same time to reduce the cost of electricity bills. The consideration of the economic assessment on the impact of the total yearly cost is evaluated for different: capacity of storage systems, user's profile regarding the consumption and the production, electricity billing schemes, and year of the investment.

As a result, the main contributions of this research and of the particular M.Sc. thesis are:

- to identify the most suitable storage technologies for the PSoC that can contribute towards the increase of RES penetration in the PSoC for the following years
- to evaluate the profitability of the investment for energy storage system installed at low voltage side. This investment will increase the self-consumption from locally produced energy and will reduce the cost of electricity.

1.3 Outline of the dissertation

The work of this MS.C. thesis is organized in seven chapters. Chapter 2 begins with the presentation of the market design of Cyprus and electricity price statistics. More specific, the three-stages markets of Cyprus electricity market are reported and the reason of high electricity price of Cyprus due to the use of conventional power plants is explained. Then, the electricity generation mix of the power system of Cyprus is presented, which is consisted of energy from conventional thermal plants and from RES. A description of the three conventional power plants and their power capacity and units, as well the renewables integration in Cyprus and their benefits is following.

An investigation of different types of energy storage technologies is presented in Chapter 3. In this chapter, the storage technologies are classified based on the process behind the conversion of energy to be stored in two main types, the mechanical and electro-chemical.

The proposed methodology for ranking the storage technologies is presented in Chapter 4. The procedure of the methodology that is followed starts with the identification of the services that ESSs can provide in smart grids to increase the RES penetration into the power system, next the identified services are classified according to their ability to assist grid services and RES integration and then the features of several storage technologies are scored in order to rank their suitability to provide the identified services based on an extensive analysis of their technical, commercial and environmental parameters in accordance with the specificities of the power system of Cyprus.

Chapter 5 explains the concept of self-consumption of solar energy. More specific, the procedure that is followed is explained based on the load demand and PV production from rooftop-PVs. Then, some results for the calculated self-consumption of a house during a year are presented and the main differences between different periods of the year are mentioned. Also, the impact of the energy storage system in the imported energy is showed.

Chapter 6 details the methodology for techno-economic assessment for the low-voltage side (behind the meter) of the power system of Cyprus. This chapter includes the classification of the network users based on the load demand and their energy production from rooftop-PVs, description of the input parameters which are used for the calculation of the electicity bill for different costing schemes and description of the scenarios which are used in the sensitivity analysis that is followed. Then, the results of the sensitivity analysis are presented. Finally, Chapter 7 includes a general discussion about this work and all the important conclusions are summarized. Also, a reference to future work related to this work is performed.

CHAPTER 2

IDENTIFY THE CASE OF CYPRUS

For the purpose of evaluating the storage technologies for the PSoC regarding their technical requirements, economic and environmental sustainability; initially the case of Cyprus, which is the case under consideration, has to be characterized. The procedure to characterize this specific case uses the year 2018 as the base-case scenario, for which there were available details as regards the power production per source type and also financial annual reports for a whole year at the beginning of this work. The method is to identify the electricity storage technologies which are the suitable in order to reduce, at different operation levels, the integration of variable RESs. Thus, in the next sub-sections are presented the market context which details the market design and the electricity price statistics, the electricity generation mix for year 2018, as well as the integration of RESs and the operation challenges which are caused from this at the power transmission level.

2.1 Market design and electricity price statistics

In 2004, the unbundling process of the energy area of Cyprus was started by a 35% opening of the market to large power producers and large industry consumers with purpose to provide competitive prices and improved services to the customers. The market for all non-domestic customers opened in 2009, which was about 65% market openness. Then, in 2010 the installation of Orites Wind Farm (82 MW) took ground, which was the first large installation of RESs in Cyprus. In 2013, the net-metering scheme started for all the new installations of rooftop PV and with this scheme the prosumers can save money by their self-consumption, while for larger power producers with installed capacity greater than 10MW the net-billing scheme is used. In 2014, the electricity market fully opened to all customers but the EAC- Supply Division currently remains the only electricity supplier within the island.

The Cyprus Energy Regulatory Agency (CERA) adopted the electricity market structure in 2015, which is the Net Pool Model [6], and Cyprus Electricity Market will be consisted of three-stages markets (currently only two are operational):

1. The *Forward Market (FM) (operational)* is dominated by two-sided contracts between power producers and electricity suppliers

2. The *Day Ahead Market (DAM) (operational*) is compatible with the algorithm of Price Coupling of Regions (PCR) and Cyprus is using a single region model for the algorithm run by the Market Operator (MO)
3. The *Intra-Day Market (not yet operational)* will correct the unexpected imbalances from the DA and is expected to become operational by the end of 2021

The TSO of Cyprus (TSOC) run the integrated scheduling process governing the electricity market.

According to the *Cyprus - Integrated national energy and climate plan for the period 2021-2030* [7], the RESs that are going to be installed have to participate in the competitive Electricity Market, where penalties will be given in the case with forecasting unbalance greater than 10%. Also, the net-metering will be replaced by an asymmetric net-billing as provided in [8]. Furthermore, the RES penetration in Cyprus is affected by the participation only of conventional generation in the electricity market, given that no regulation for the capacity established yet.

The EAC dominates the Cyprus' electricity area with the operation of three conventional power plants. These plants are based on fully imported oil and as a result Cyprus has the highest electricity prices in Europe for non-house-hold consumers, as shown in Figure 1 for the year 2018. Although the full opening of the electricity market, the EAC remains the only supplier.

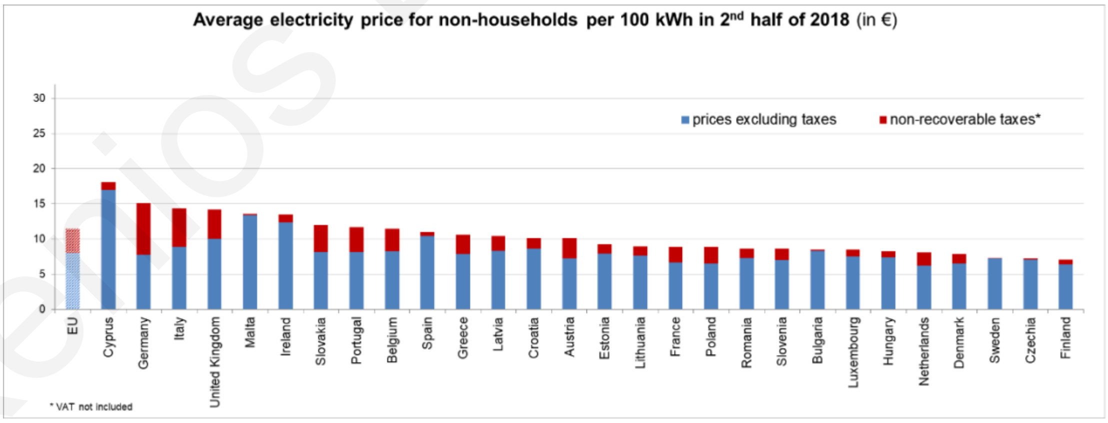


Figure 1: Average electricity prices for non-household consumers in Europe 2018 [9]

Regarding the ESSs, in the Cyprus' regulatory framework [10] is mentioned that "storage systems installed upwards the metering point and which are not combined with local consumption of electricity could potentially participate in the Wholesale Electricity Market, at all stages of the market". So, the ESSs which are installed at grid level can go either on two-sided contracts with RES IPP and/or aggregators of RES and participate in the FM or DAM or both.

2.2 Electricity generation mix

The PSoC is an isolated power grid and as a result has a limited capability to react to contingencies and events, such as a relatively low inertia and low operation flexibility, which is common for power grids within the European context, and more specific to Mediterranean insulated power grids such as Crete in Greece or Madeira in Portugal. Moreover, in the PSoC is presented highly daily and seasonal demand fluctuation, and the grid is not connected to neighbor countries.

The most of electricity power production within the island is produced by conventional thermal power plants operating fully with imported fossil fuel, mainly heavy fuel or diesel in a smaller proportion. The Electricity Authority of Cyprus (EAC) is the owner of the existing thermal generation capacity and provides approximately 90% of the total electricity generation on the island and the rest electricity generation is provided from the RESs [3].

The thermal power generation fleet of the PSoC includes steam turbines, combined cycle gas turbines, internal combustion compression ignition engines and gas turbine units, and its total installed capacity is 1478 MW. They are concentrated in three sites: Vasilikos, Dhekelia and Moni power plants. Vasilikos is the largest power plant with a total installed capacity of 868 MW. Dhekelia is the second largest power plant with a total installed capacity of 460MW and Moni power plant is the smallest with a total installed capacity of 150 MW. The share of conventional power capacity for each plant owned by the EAC is given in Figure 2.

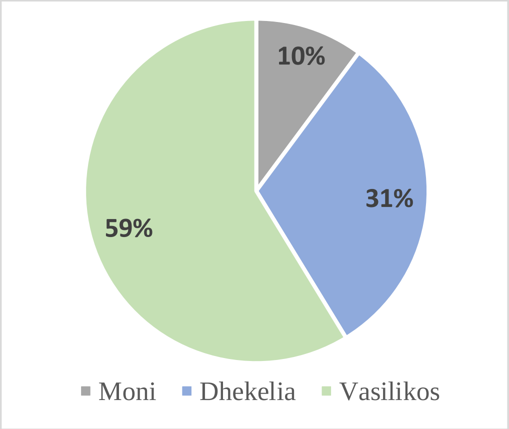
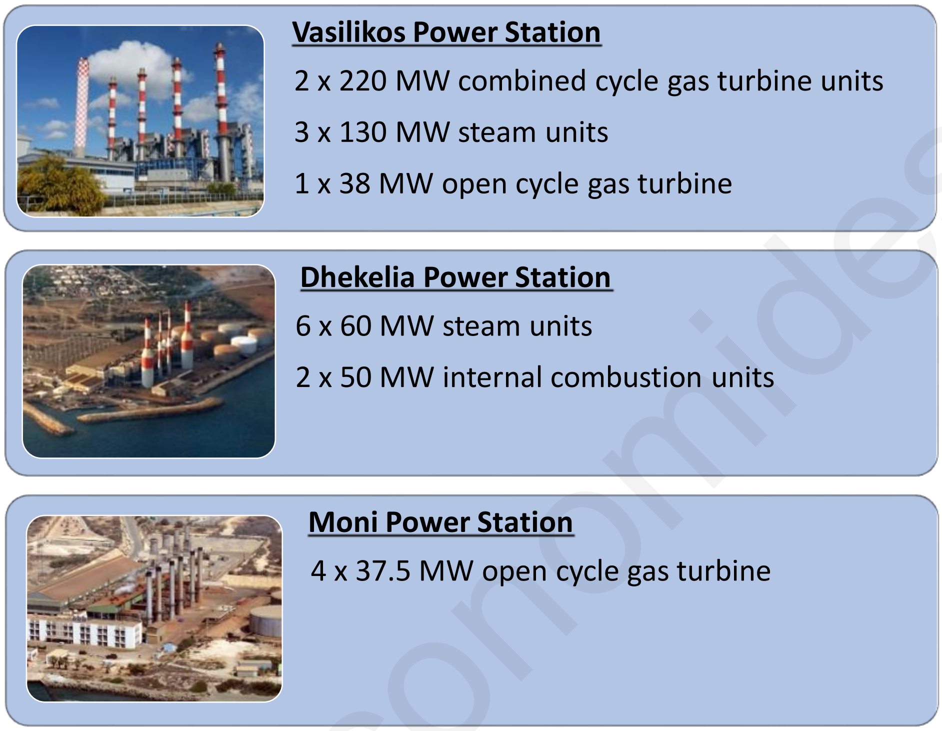


Figure 2: Plant share from the total conventional power capacity owned by the EAC

As base-load units are used the Vasilikos' combined cycle units which are the most modern and efficient thermal units on the island. The steam turbine units of Dhekelia will be retired at the end of 2023 and the fleet of Moni is used only for peak hours and emergency times. In Figure 3, the units if each power plant are presented.



Vasilikos Power Station

2 x 220 MW combined cycle gas turbine units

3 x 130 MW steam units

1 x 38 MW open cycle gas turbine

Dhekelia Power Station

6 x 60 MW steam units

2 x 50 MW internal combustion units

Moni Power Station

4 x 37.5 MW open cycle gas turbine

Figure 3: Cyprus' power plants and their units

2.3 Renewable energy integration

As regards the RESs present in Cyprus, at the end of 2020, the largest share was coming from the photovoltaics (PV) with 229.1 MW installed capacity at MV and LV side of DSO [3] which is expected to increase significantly, according to the strategic plan for climate change of Cyprus [7]. The share of the in-land wind power farms (WF) was significant with 155.1 MW installed capacity at HV transmission network, TSO side of the power network, and 2.4 MW installed at MV distribution network, DSO side of the power network. The installed capacity of biomass is only 12.1 MW at MV lines power distribution network, DSO side of power network. The share of RESs from the total electricity production in PSoC for the year 2020 is 11.7% which was 9.7% on December of 2019 and 9.0% in the end of 2018. The PVs and WFs are characterized by their variability and as a result the prediction of their power output during a day is difficult. Moreover, they have limited operation flexibility which makes difficult the following of load demand and capacity firming options in the day-ahead market.

Renewables are not allowed to participate in ancillary services of PSoC, but they may be subject to mandatory obligation to reduce production (active power curtailment) due to system stability concerns, in the case of system's operation near minimum stable operation of the must-run units which is happening in periods with low load and high RES production. The RESs, despite these restrictions and operation challenges they may pose to the system operator, provide various benefits to society, such us the:

- reduction of CO_2 emissions by replacing power generation that would otherwise be produced by conventional power plants
- help to reduce and smooth the peak of the net-load demand (Figure 4) because of the high solar irradiation and clear sky during the period of summer. Moreover, the need of the use of expensive to operate, peak conventional power units is reduced.

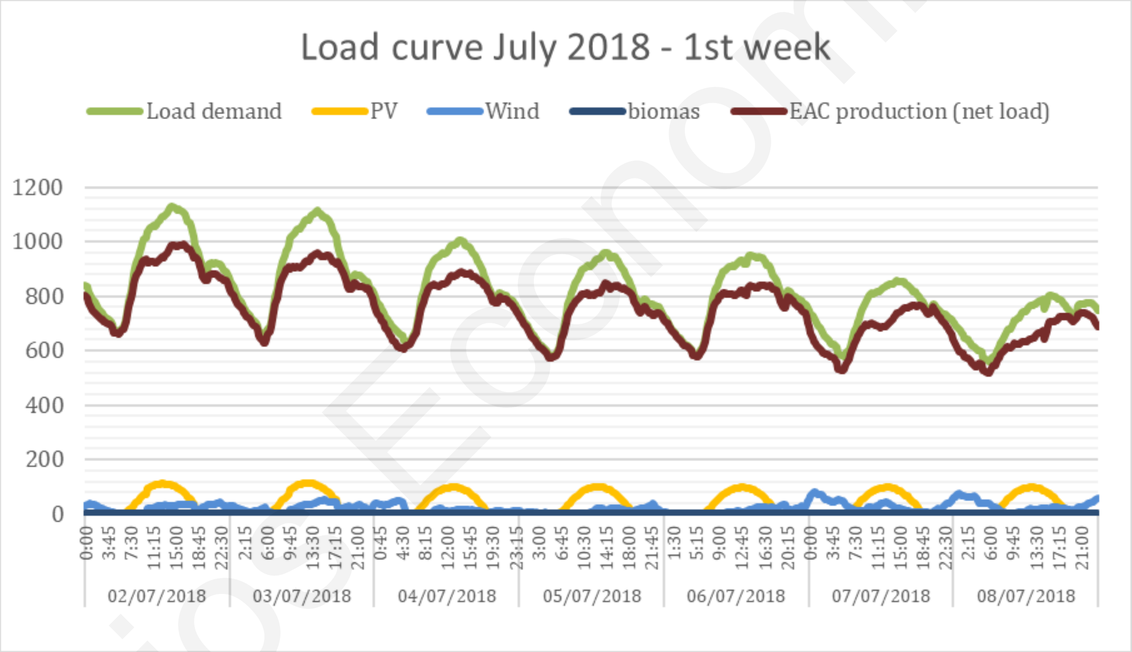


Figure 4: RES contributing to peak net-load demand reduction during summer [11,12]

CHAPTER 3

TYPES OF ENERGY STORAGE TECHNOLOGIES

In this thesis, the classification of the examined storage technologies suitable for grid level and behind the meter (BTM) distributed storage technologies is depending on IRENA's [1] report. In Table 1 is presented a summary of the classification. The following description of each technology emphasizes on the technical, commercial and environmental characteristic was carried out following an extended literature review including international agencies reports, scientific literature and commercial data sheets.

Table 1: Classification of examined electricity storage technologies

Mechanical storage	Pumped Hydro Storage (PHS), Compressed Air Energy Storage (CAES), Flywheels
Lead-acid batteries	Valve-Regulated Lead Acid (VRLA)
High-temperature batteries	Sodium nickel chloride batteries (NaNiCl), Sodium sulphur batteries (NaS)
Flow batteries	Vanadium Redox Battery (VRB), Zinc Bromine Battery (ZBB)
Lithium-ion batteries	Lithium Nickel Manganese Cobalt batteries (NMC), Lithium Nickel Cobalt Aluminium batteries (NCA), Lithium Ferro Phosphate batteries (LFP), Lithium Titanate Oxide batteries (LTO)

The mechanical storage and electro-chemical storage are the two mainly types of storage technologies based on process behind the conversion of energy to be stored. The electro-chemical storage can be classified into other groups as they presented in Table 1. Moreover, except the above technologies, other technologies are existing such as the Hydrogen and Gravity Energy Storage Systems which are not examined in this work.

3.1 Mechanical Storage

Mechanical energy storage systems (MESSs) have as main advantage the flexibility in operation and conversion of the stored energy from several type of sources. Based on the working principle, MESSs can be classified as: pressurized gas storage, forced spring storage, kinetic energy storage, and potential energy storage systems. However, from a technological point of view, mechanical storage systems consist of three types: the flywheel, the pumped hydro storage, and compressed-air energy technologies [13].

Flywheel energy storage system (FESS) is a massive rotating disk or rotor that is supported on a stator by magnetically levitated bearings. Flywheels with speed of under 10.000 rotations per minute (rpm), which are popular within several industries, are considered as low-speed flywheels. A flywheel can be used for the smooth running of machines and can mechanically store kinetic energy from the rotor mass spinning at high speeds. The stored kinetic energy in FESS is related to speed and inertia. Low speed FESS contains a steel disk with high inertia and low speed. High-speed FESS has a disk with relatively lower inertia and high speed. As the rotating speed of rotor increases, stored energy also increases proportionally, and the stored energy varies in a square with angular momentum. This stored energy can be used further by decelerating rotor torque, discharge mode, and returning the kinetic energy to the electrical motor, which acts as a generator. Moreover, flywheels can be added in parallel to increase the specific energy. The energy concentration varies from low (5 Wh/kg) speed to high (100 Wh/kg) speed [14]. FESS stores the electrical energy in the rotating mass. The efficiency of FESS is greater than 80% and their cycles life is about 20.000. The main advantage of FESS is that it requires no temperature control equipment [1]. The major disadvantages of this system are that a FESS can only supply enough power with a modest capacity for a short period of time, thus making it an ineffective solution for energy backup in standalone power applications. Additionally, FESS suffers from losses due to high self-discharge which could go up to 20% of the stored capacity per hour during the idle period when the flywheel is on standby [15].

Pumped hydro storage (PHS) is a large-scale energy storage system. The operation of PHS depends on the gravitational potential energy of water during a flow from a higher water reservoir to a lower water reservoir [16]. The water is pumped into the upper reservoir during the periods with off-peak electricity demand or when the RESs supplies more energy than the load demand (curtailment avoidance). The PHS can generate up to 3.000 MW of electricity for utility purpose [15] with efficiency mainly between 65% and 80% [17], while its maximum depth of discharge is about 80% without affecting its service period, which could go up to 50.000 cycles life [1]. The main disadvantage of this technology is the restriction of site location because of the large size of the higher water reservoir above the ground.

Compressed Air Energy Storage (CAES) stores energy in air by compressing the air to a very high pressure. During low power demand, the excess energy which is supplied from renewable sources or from the grid system is utilized to drive a reversible motor or a generator unit, which in turn powers a chain of compressors to inject the air into the storage unit. During low power generation for the load demand, the compressed air which is under a high pressure is heated in the combustor and finally transferred to a gas turbine to generate electricity. There is a by-product during the process which can be recycled into the system using a recuperator for heating the compressed air. A large scale CAES is usually used for load shifting, frequency and voltage controlling grid applications. The efficiency of CAES is about 60% with 50.000 cycles life [1]. The disadvantages of this system include a relatively low round trip efficiency when compared to PHS and battery technologies and the appropriate geographical location for installation of the plant which has a high implication on the overall investment [18].

3.2 Electrochemical energy storage systems - Batteries

The storage for electrochemical energy is otherwise known as the Battery Energy Storage System (BESS) as it uses rechargeable batteries for energy storage. A rechargeable battery consists of one or more electrochemical cells, which can store and generate electric energy, with external connections to power electrical devices. A rechargeable battery has: a positive electrode (cathode) which accepts electrons and through which current flows into a polarized electrical device; a negative electrode (anode), which produces electrons from which a current leaves a polarized electrical device; and an electrolyte which is a substance able to provide an electrical conduction of electrons between the anode and the cathode. The battery converts chemical energy into electric energy during discharge. During charge, this reaction is reversed and a corresponding amount of energy from an external source has to be supplied to the cell [19]. In the analysis of this work, the *Lead-acid batteries*, two types of *high-temperature batteries*, *flow batteries* and *Lithium-Ion* batteries are considered.

Lead-Acid Batteries are based on chemical reactions involving lead dioxide, lead and sulfuric acid. Their negative electrode is metal lead and the positive electrode is lead dioxide, while the internal resistance of the cell increases through the separators which obstruct the flow of ions between the plates. The operation of these batteries is based on the principal of oxygen recombination, using an immobilized electrolyte. The oxygen generated at the positive electrode during charge can diffuse to the negative electrode, where it can react, in the presence of sulfuric acid, with the freshly formed lead. The charge-discharge process of lead-acid battery is essentially reversible [15]. This is technology is uncomplicated and its efficiency is about 80% [1]. Despite having a low capital cost [1], [18], such batteries are slow to charge, cannot be fully discharged and have a small number, about 1.500, of charge/discharge cycles and a low energy-to-volume ratio (30-50 Wh/kg). The lead acid used are also highly toxic and may create environmental hazards [15].

High-Temperature Batteries includes the Sodium Nickel Chloride battery and the Sodium Sulfur battery. The basic cell structure of ***Sodium Nickel Chloride battery*** consists of an anode part, made by molten sodium (Na), a solid ceramic electrolyte, namely beta-alumina and a cathode part made by Nickel Chloride ($NiCl_2$) with the addition of metallic doping substances. One of the main features of this technology is that its solid electrolyte presents a very low ionic resistivity in the temperature interval between 250 ^{o}C and 300 ^{o}C, with an operating temperature equal to 260^{o}C [20]. The efficiency of this battery is about 85% with life about 3.000 cycles [1].

Sodium sulfur **(NaS)** batteries consist of molten sulfur at the positive electrode and molten sodium at the negative electrode separated by a solid beta alumina ceramic electrolyte. The electrolyte allows only the positive sodium ions to go through it and combine with the sulfur to form sodium polysulfides. During discharge, positive sodium ions flow through the electrolyte and electrons flow in the external circuit of the battery producing about 2V [19]. The efficiency of NaS batteries ranges between 70% to 85% with very low self-discharge and a number of cycles life of about 5000 [1]. The NaS batteries offers solutions for many large-scale electric utility energy storage applications, such as load leveling, power quality and peak shaving, as well as renewable energy management and integration. However, because of the operating temperatures of 300–350 ^{o}C and the highly corrosive nature of the sodium polysulfide discharge products, such cells are primarily suitable for large-scale, non-mobile applications such as grid energy storage [13].

Flow Batteries store energy in two different aqueous electrolytic solutions contained in separate tanks. A flow battery's operation is based on reducing-oxidation reactions that occur in the separate electrolyte solutions. During the battery charging, the electrolyte in one tank is oxidized at the anode, while the other electrolyte in the other tank is reduced at the cathode, while this process is reversed during the discharging phase. Two common flow batteries which are commercially available are ***Vanadium Redox Battery (VRB)*** and ***Zinc Bromine Battery (ZBB)*** [15].

The VRB is a type of rechargeable flow battery that employs vanadium ions to store chemical potential energy and is a particularly clean technology. The main characteristics of VRB is the high availability and a long-life, about 13.000 cycles. Its energy density is very low, about 7 Wh/kg. The VRB is able to offer almost unlimited capacity by using aggregation of large storage tanks and it can be left completely discharged for long periods with no bad effects. As disadvantages of VRB are the low energy-to-volume ratio and the complexity of the system compared with other batteries. The VRB is well suited for use in large power storage applications, because of its large capacity, such as helping generators cope with large surges in demand. Moreover, the VRB is useful in applications where the batteries must be stored for long time (due to their low self-discharge ratio), while it also needs little maintenance.

ZBB is a type of hybrid flow battery and is stored in two tanks. When the battery is charged or discharged, the solutions are pumped through a reactor stack and back into the tanks in which the electrolytes are stored. In one tank, the positive electrolyte is stored and in the other tank the negative electrode. The energy density of ZBB from different manufacturers ranges from 34.4 to 54 Wh/kg with 100% depth of discharge capability on a daily basis and high cycle life, up to 10.000 cycles. Moreover, the capacity of ZBB is scalable from 10 kWh to over 500 kWh systems and is able to store energy from any electricity generating source [1], [13].

Lithium-ion Batteries have a negative electrode (cathode), which is a lithiated metal oxide, composed of a copper collector on the faces of which is deposited the active material, an anode which is made of graphitic carbon with a layer structure, and a polyethylene separator generally avoiding contact with the positive electrode consists of an aluminum current collector coated material active lithium insertion. In the case of Li-ion batteries, the main mobile species in a Li-ion accumulator is Li+ cation. After charging the battery, the Li atoms become Li+ and migrate towards the carbon anode where they combine with external electrons. During the discharge, this behavior is reversed. The main advantages of these batteries are their high energy density and the energy efficiency which is greater than 85% [1], [19]. Their cycles life ranges between 1.000 cycles and up to 10.000 cycles, depending on the battery type. There are various types of lithium-ion batteries in commercial use, such as cobalt, manganese, titanate and phosphate.

Hydrogen Energy Storage is a type of chemical energy storage in which electrical power is converted into hydrogen. This energy can then be released again by using the gas as fuel in a combustion engine or a fuel cell. Hydrogen can be produced from electricity by the electrolysis of water. The hydrogen must then be stored, potentially in underground caverns for large-scale energy storage, although steel containers can be used for smaller scale storage. The round trip efficiency of this technology is lower than other storage technologies. Despite this low efficiency the interest in hydrogen energy storage is growing due to the much higher storage capacity compared to small and large scale storage technologies, such as batteries or PHS and CAES [21]

Gravity Energy Storage is an electrical storage device that stores gravitational energy, the energy stored in an object resulting from a change in height due to gravity. A type of gravity battery is one that releases a mass, such as a block of concrete, to generate electricity. The excess energy from the grid is used to raise a mass to generate gravitational potential energy, which is then dropped to convert potential energy into electricity through an electric generator. The lifespan of this storage technology is 50 years, its efficiency is 80 – 90% and it has fewer environmental issues than other storage solutions. It is expected that gravity battery systems will be able to quickly provide power during peak consumption which may allow them to supplement or replace fossil fuel peaking power plants [22].

CHAPTER 4

METHODOLOGY FOR RANKING THE STORAGE TECHNOLOGIES

The target of this analysis is to restrict the options of the suitable storage technology to address the operation challenges of the PSoC. Thus, the procedure of the methodology that is followed is:

1. Identify the services that ESSs can provide in smart grid to increase the RES penetration into the power system
2. Classify the identified services according to their ability to assist grid services and RES integration
3. Score the features of several storage technologies in order to rank their suitability to provide the identified services based on an extensive analysis of their technical, commercial and environmental parameters in accordance with the specificities of the power system of Cyprus

4.1 Services by Energy Storage Systems in Smart Grid

Generally, the combination of an electrical network with a dedicated ICT (Information and Communication Technology) control infrastructure constitutes a smart grid. The ICT control infrastructure increase the flexibility of the network. Thus, new energy managements approaches will be turned up through the forthcoming deployment of the smart grids. The target of these managements is to increase the share of RESs in the energy mix.

The procedure to identify the energy storage services, which help the country to achieve its target to increase the RES penetration, is based mainly on IRENA’s Framework for Storage Valuation [1]. The mapping of storage technologies with specific services might be changing over time, as new technologies and services will be developed in the future. However, for a given project is required to be assessed only one time at the initial stage of the storage valuation exercise.

In Table 2 are presented the identified services which could be delivered by ESSs within the electricity production chain. The classification was tailored to the specific Case of Cyprus and adapted according to the most accurate available information. Thus, the service of Transmission and Distribution (T&D) investment deferral is not included in this thesis compared to IRENAS’s Framework, because the transmission network of Cyprus is relatively strong and no specific thermal limits of the equipment were identified as challenges due to increased capacity of RESs, while for the distribution network there no available data for scoring the services related to deferral of investment in distribution network upgrades needed in a scenario with high RESs.

Table 2: Quantifiable energy storage services

Bulk Energy Services	Ancillary Services	Costumer Energy Management Services
• Renewable energy time-shift	• Fast frequency response • Operating and replacement reserves • Renewable smoothing • Flexible ramping • Reactive power management	• Power reliability • Behind The Meter (BTM) power management

The identified services are the following:

4.1.1 Renewable Energy Time-shift

The aim of energy time-shift is to purchase less expensive electricity available during periods when demand is low, to charge the storage plant, so that the low-priced energy can be used or sold at a later time when the electricity is expensive. The duration so that the result of this operation is visible is a whole day due to, mainly, the energy is shifting from periods of high demand during the noon to low demand periods at night. The ability of the different storage technologies to perform these functions varies depending on their state of charge, their charging/discharging capability, and their energy storage capacity. An advantage from providing energy time-shift service is the reduction of RES curtailment when generation exceeds load demand [23].

4.1.2 Fast Frequency Response – Operating and Replacement Reserves

Reserves are defined as the extra capacity over the capacity needed to be equal with the existing load demand, which is made available to support in case of load increase or generation decrease. In the case of Cyprus power system, reserves are divided into: (1) frequency containment reserves, which are used to stop the frequency deviation and recover frequency at 49.5 Hz and need to act within 3 seconds; (2) the frequency restoration reserves, which need to act within 20 seconds to restore the frequency from 49.5 Hz to 49.8 Hz within 20 seconds; and (3) the replacement reserves which are used to restore the frequency to its nominal value and acts within 20 minutes (Figure 5). Energy storage is a great resource to provide operating reserves, as it is able to provide full output in less than a second and its idle costs are low. Batteries can provide a faster response than other products, such as gas turbines and thermal generators. As a result, multiple units of conventional frequency containment reserve products can be replaced with a single and quick to react unit, while within electricity market a pay-for service product could be made available for Fast Frequency Response [10].

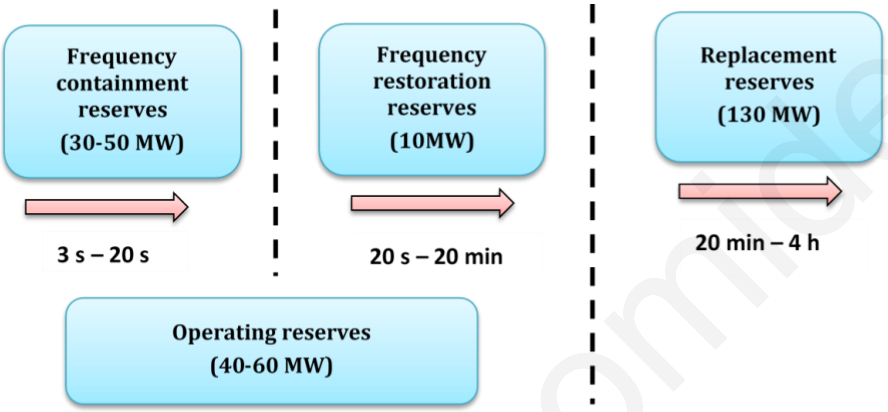


Figure 5:Operating and replacement reserves of Cyprus' power system

4.1.3 Renewable Smoothing

Many RESs provide power intermittently on a minute-to-minute basis [23] and because of their variability and uncertainty, they have a fluctuating non-dispatchable output, as shown in the grey cycles in the Figure 6. The power fluctuations from solar PV mostly are due to the movement of clouds, and more specifically, when a cloud covers an array of PV panels from the sun, the energy production of that array will drop during that period and will increase once the cloud passes, while the variability of wind speed is the cause of power fluctuation from wind. Instability in voltage and frequency created from power fluctuations, in small isolated power systems could affect their reliability and security and can have negative effects, such as transmission and distribution loading and voltage fluctuations [1], [23].

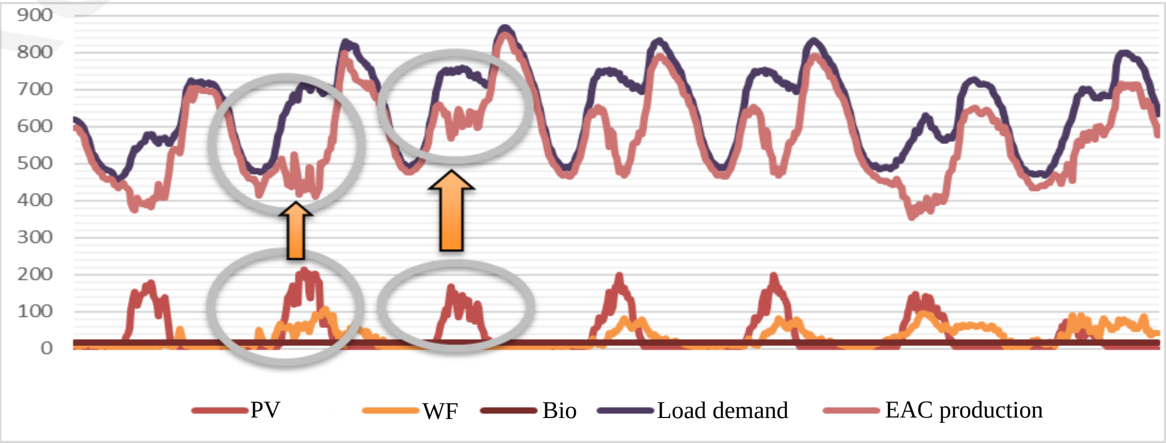


Figure 6: Renewable fluctuations for the Case of Cyprus [11,12]

A solution for system operators to smooth the RES production is energy storage. The energy storage, due to its ability for quick respond to changes, when it is connected with RES resources has the ability to smooth the fluctuations of RESs, avoid frequency and voltage fluctuations, avoid RES curtailment and improve the system's reliability. In order to be clear how the energy storage operate for this service, assume that there is a ramp limitation (*Rmax*) in the system and a RES power variation (ΔP) for a short duration period. If ΔP exceeds the *Rmax* and is positive, energy storage will absorb the extra energy that otherwise would be curtailed, and if ΔP is negative the energy storage will discharge the stored energy in order to avoid loss of load. The duration so that the result of this operation is visible in some minutes because of the importance to cover the need of the system operators to maintain grid stability.

4.1.4 Flexible Ramping

The load curve represents the required energy of the customers in every time. In the case of low penetration of RES in the power system, the main characteristic of load curve is the two peaks that are appearing in the morning and in the evening, the called "camel curve" (Figure 7). This curve is predictable, and the ramping requirements are smooth. However, in power system where the RES penetration is high, the load curve is reshaped to the called "duck curve" because of the variability of these resources (e.g. high PV penetration). The main characteristic of this curve is the high ramp requirements that can cause a reliability issue and the system operators need a resource mix that can react quickly to adjust production and cover the steep changes in net demand. Energy storage could be a solution to cover these ramp requirements and to flatten this curve given its capabilities to quickly absorb and discharge energy [1].

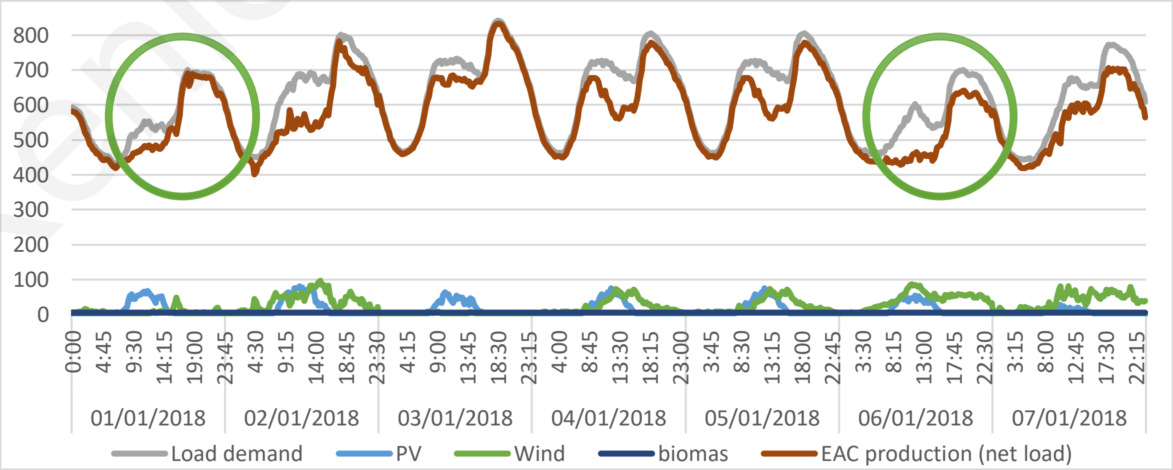


Figure 7: Load curve and production of Cyprus for the first week in January 2018 [11,12]

The operator, in order to calculate the ramping requirement in Period 1, has three options of operation in Period 2 which correlate with the expected net load in the next period and the uncertainty of this net load (higher or lower). If the uncertainty upwards had been higher than the net load in Period 1, the requirement is flexible ramping up and if the uncertainty downwards had been lower than the net load in Period 1, the requirement is flexible ramping down (Figure 8).

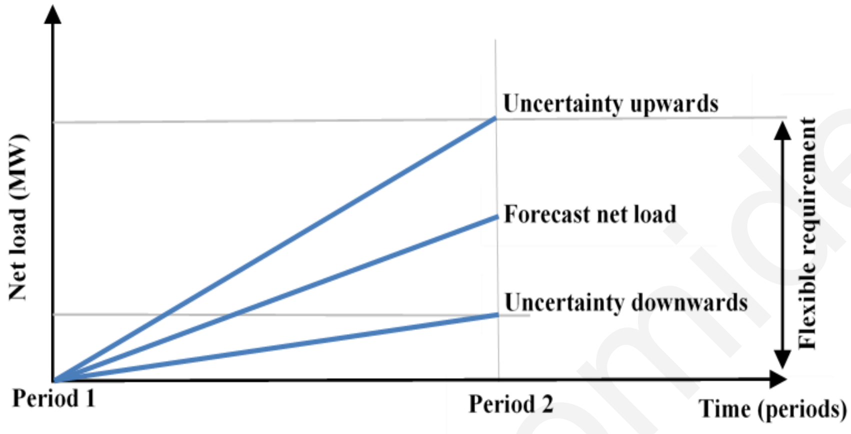


Figure 8: Calculation of ramp requirement

4.1.5 Reactive Power Management

The maintain of voltage within an acceptable range is a requirement for electric grid operators, which means that the management of reactance is required. In order to manage reactance at the grid level, system operators need voltage support resources to offset reactive effects so that the transmission system can be operated in a stable manner. Strategically placed energy storage within the grid at central locations or placing multiple reactive power-support storage systems near large loads, can replace the designated power plants which are used to generate reactive power to offset reactance in the grid (Figure 9).

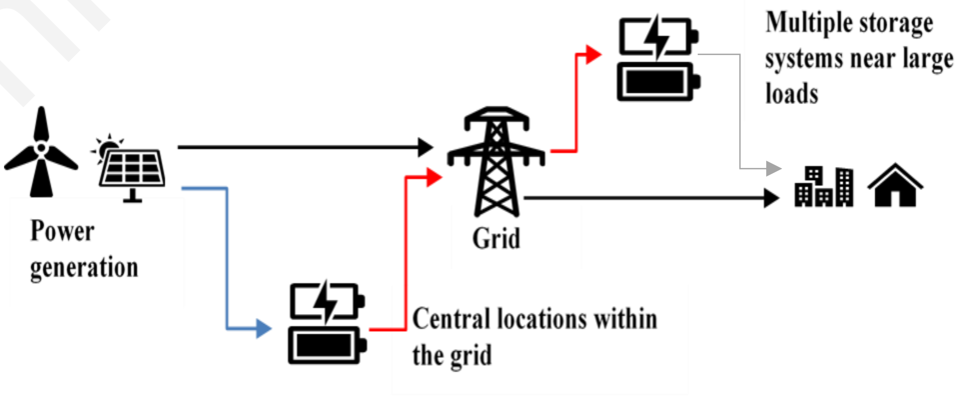


Figure 9: The location of energy storage systems to manage reactive power

4.1.6 Power Reliability

Energy storage is used to improve the reliability of electric service. When a power outage occurs with duration more than a few seconds, the storage system provides enough energy in order to ride through outages of large duration, to complete an orderly shutdown of processes and/or to transfer to on-site generation resources. The required duration of discharge depends on the kind of the situation. An example of power reliability product could be the Uninterruptible Power Supply (UPS) [24].

4.1.7 Behind The Meter (BTM) Power Management

BTM storage can reduce electricity bills and demand charges and provide backup power. The excessed energy which cannot be used at a specific time can be absorbed by energy storage, and later be made available for use when required. The combination of energy storage with rooftop solar PV increases the self-consumption, the excessed energy during the day can be absorbed and used when the production of solar PV is not enough in order to cover the demand. This type of energy storage is usually referred to as behind-the-meter storage because it is located downstream of the connection point between the utility and the customer [1]. In Figure 10, it is shown how a BSS with a capacity of 4.5 kWh affects the self-consumption during month of October in Cyprus, and how the imported energy is reduced when the PV system is combined with BSS. The state of charge of the battery is presented in the right figure and it is shown that the battery is charged when there is excessed energy from the PV production, and it is discharged when there PV production is lower than the load demand.

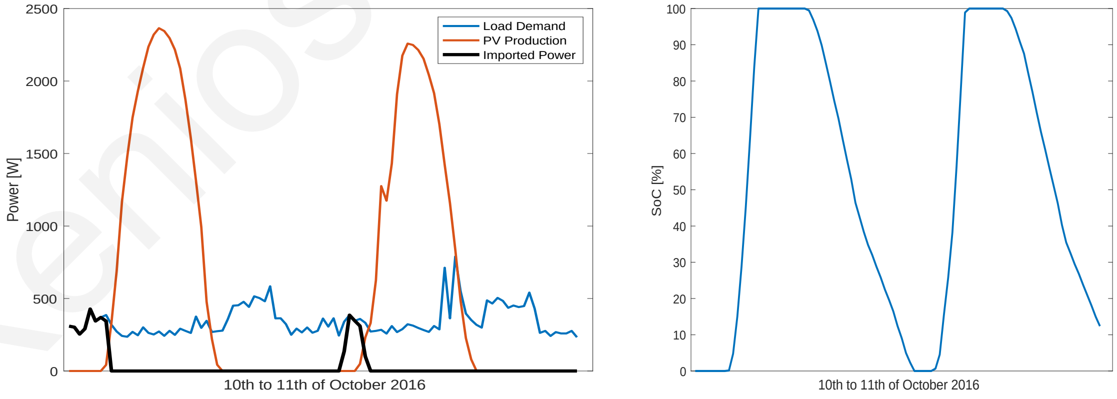


Figure 10: Self-consumption with installed energy storage coupled with solar PV

4.2 Ranking of Storage Technologies

In order to determine the suitability of several technologies, inputs from experts in storage technology are required. The necessary information are the attributes and scoring criteria that are applied to each technology. The storage technologies are ranked through the following methodology, based on various technical, commercial and environmental parameters for each service. In the following diagram (Figure 11) is presented the methodology that is followed in order to rank the energy storage technologies:

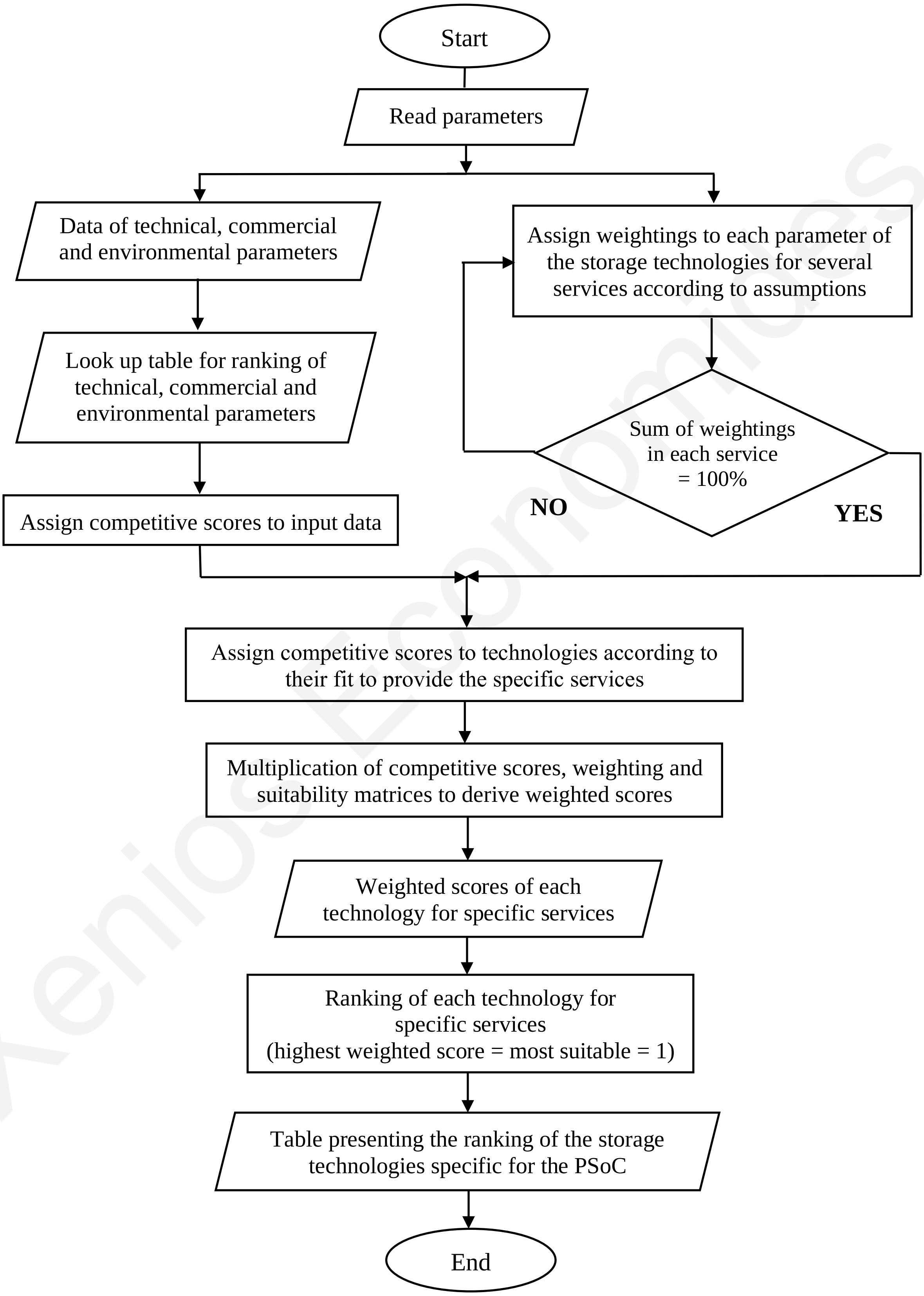


Figure 11: Methodology of ranking the energy storage technologies

Different technologies are scored by weighting characteristics compared with their affinity in certain applications, and in order to determine how suitable is a technology in a specific application the matrices with the results are used. Through this section, the storage technologies are ranked based on their ability to provide the services which are identified in the previous section.

4.2.1 Assigning Competitive Scores to Technologies

The main technical, commercial and environmental parameters of the selected energy storage technologies were derived from [1], [25], and they are summarized in Table 3.

Table 3: Technical, commercial and environmental parameters of energy storage technologies

Technical	Commercial	Environmental
• Efficiency (AC-to-AC) • C-rate minimum • C-rate maximum • Maximum depth of discharge • Maximum operating temperature • Safety (thermal stability) • Energy density • Power density	• Storage CAPEX • Power converter CAPEX • Development and construction time • Operating cost	• Climate change - Human health • Human toxicity • Particulate matter • Fossil resource • Climate change - Ecosystems

These parameters will be weighted and scored based on their importance for each service, as well as their value as a comparison between ESS technologies. Then, each technology can be scored and ranked according to its suitability for each service. For the later, a calculation of a weighted average score will take place, while the ranking will be made from the highest to the lowest summation of the weighted average score for each ESS technology type.

Table 4 provides the values for each technical and commercial characteristics per type of storage technologies [1], as well as the evaluated scores of the environmental parameters of these technologies [25]. The data for the Storage CAPEX, Power Conversion (PCS) CAPEX, and the operating costs were converted from US dollars to euros using the conversion rate of 1 dollar ($) equal to 0.93 euro (€). The Initial capital cost is calculated as the sum of the Storage CAPEX and PCS CAPEX, while the environmental impact is calculated as the sum of all environmental parameters. Regarding to C-Rate, the scores are based on the ratio between the power rating and the energy rating of a storage device. At full power, 1C means that the storage will be depleted in 1 hour. A 2C score means that the duration for fully discharge is 30 minutes, while C/2 means that the duration for full discharge is 2 hours.

Table 4: Technical, commercial & environmental parameters of ESS technologies

	Lead -acid	Mechanical Storage			Lithium-ion Batteries				High-temperature Batteries		Flow Batteries	
Parameters	**VRLA**	**Pumped Hydro**	**CAES**	**Flywheels**	**NMC**	**NCA**	**LFP**	**LTO**	**NaS**	**NaNiCI2 (Zebra)**	**ZBB**	**VRB**
Technical												
Efficiency (AC-to-AC) (%)	82	80	60	84	92	92	86	96	80	84	70	70
C-Rate min	C/10	C/20	C/10	1C	C/4	C/4	C/4	C/4	C/8	C/8	C/8	C/8
C-Rate max	2C	C/6	C/4	4C	2C	1C	2C	10C	C/6	C/6	C/4	C/4
DoD (%)	60	80	80	90	90	80	90	90	80	80	100	100
Max. Operating Temperature (º C)	50	NA	NA	NA	55	55	65	65	Na	NA	45	50
Safety (Thermal Stability)	High	NA	NA	NA	Medium	Low	High	High	Medium	Medium	Medium	High
Energy Density (Wh/kg)	40	NA	NA	22	180	200	130	75	65	55	40	7
Energy Density (Wh/L)	90	NA	NA	10	420	450	270	175	40	35	35	4
Power Density (W/kg)	10	NA	NA	100	40	40	25	600	8	6	12	2
Commercial												
Storage Capex (€/kWh)	137	20	49	2790	391	327	538	977	488	371	837	323
PCS Capex (€/kWh)	279	781	879	279	279	279	279	279	279	279	279	1220
Initial capital cost (€/kWh)	416	801	928	3069	670	606	817	1256	767	650	1116	1543
Development & Construction (Years)	0.25	5	3	0.5	0.25	0.25	0.25	0.5	0.5	0.5	1	1
Operating Cost (€/kWh)	2.8	1.9	0.9	74	5.6	5.6	5.6	5.6	7.4	7.4	18.6	19.5
Life (Cycles)	1500	50000	50000	20000	2000	1000	2500	10000	5000	3000	10000	13000
Maturity of Technology	M	M	C	EC	C	C	C	EC	C	D	P	D
Environmental												
Climate change – Human health (Pt/kWh)	0.009	0.008	0.009	NA	0.008	0.008	0.008	0.008	0.007	0.007	NA	NA
Human toxicity (Pt/kWh)	0.003	0.001	0.001	NA	0.003	0.003	0.003	0.003	0.001	0.003	NA	NA
Particulate matter	0.002	0.001	0.001	NA	0.002	0.002	0.002	0.002	0.001	0.004	NA	NA
Fossil resource (Pt/kWh)	0.01	0.008	0.01	NA	0.011	0.011	0.011	0.011	0.007	0.007	NA	NA
Climate change – Ecosystems (Pt/kWh)	0.006	1	0.006	NA	0.005	0.005	0.005	0.005	0.005	0.004	NA	NA
Environmental impact (Pt/kWh)	0.03	0.024	0.027	NA	0.029	0.029	0.029	0.029	0.021	0.025	NA	NA
Environmental impact	High	Very High	Medium	Medium	High	High	High	High	Low	Medium	Low	Low

Legend for Table 4: M=Mature; C= Commercialisation; EC=Early Commercialisation; D=Demonstration; P= Prototype

The technical parameters of the energy storage technologies include AC-to-AC efficiency, energy density, power density, minimum and maximum C-rate, depth of discharge (DoD), maximum operating temperature and safety. The commercial parameters consist of PCS, CAPEX, the duration for project development and construction, operating costs, operating life and maturity of technology, while the environmental parameters include the impact to human health and ecosystems, human toxicity, particulate matter and fossil resource.

Table 5: Look-up table for competitive scores according to performance of each parameter

Score	5	4	3	2	1
Technical					
Efficiency	> 95 %	86.25 – 95 %	77.5 – 86.25 %	68.75 – 77.5 %	< 60 %
C-rate	1C and above	C/2 – 1C	C/4 – C/2	C/8 – C/4	C/8 and lower
DoD	> 95 %	86.25 – 95 %	77.5 – 86.25 %	68.75 – 77.5 %	< 60 %
Commercial					
Initial capital cost	< 500 €/kWh	500 – 850 €/kWh	850 – 1200 €/kWh	1200 – 1550 €/kWh	> 1550 €/kWh
Development & construction	6 months and less	6 – 16.5 months	16.5 – 27 months	27 – 37.5 months	4 years and longer
Operating cost	Lowest of all technologies				Highest of all technologies
Space required	> 500 Wh/kg	382.5 – 500 Wh/kg	265 – 382.5 Wh/kg	147.5 – 30 Wh/kg	< 30 Wh/kg
Life	Longest of all technologies				Shortest of all technologies
Maturity of technology	Mature	Commercialisation	Early Commercialisation	Demonstration	Prototype
Environmental					
Environmental impact	Lowest of all technologies	Low	Medium	High	Highest of all technologies

Table 6: Assignation of competitive scores to each parameter per technology type

	Lead-acid	Mechanical Storage			Lithium-ion Batteries				High-temperature Batteries		Flow Batteries	
Parameters	**VRLA**	**Pumped Hydro**	**CAES**	**Flywheels**	**NMC**	**NCA**	**LFP**	**LTO**	**NaS**	**NaNiCl2 (Zebra)**	**ZBB**	**VRB**
Technical												
Efficiency	3.4	3.2	1	3.7	4.6	4.6	3.9	5	3.2	3.7	2.1	2.1
C-rate	5	2	2	5	5	4	5	5	2	2	2	2
DoD	1	3	3	4	4	3	4	4	3	3	5	5
Commercial												
Initial capital cost	5	4.1	3.8	1	4.5	4.7	4.1	2.8	4.2	4.6	3.2	2
Development & construction	5	1	2.1	4.7	5	5	5	4.7	4.7	4.7	4.2	4.2
Operating cost	4.9	4.9	5	1	4.7	4.7	4.7	4.7	4.6	4.6	4	4
Space required	1.5	1	1	2.3	3.3	3.3	3	3.3	1.3	1.2	1.2	1
Life	1.1	5	5	5	1.3	1	1.4	3.6	2.1	1.6	3.6	4.4
Maturity of technology	5	5	4	3	4	4	4	3	4	2	1	2
Environmental												
Environmental impact	2	1	3	3	2	2	2	2	5	3	4	4

As regards the environmental impact, the Pumped Hydro is not suitable for the case of Cyprus due to its high impact in the ecosystem. The flywheels are environmentally friendly since the material used is not hazardous to the environment [26], while the flow batteries have the lowest environmental impact compared to other technologies in [24].

Each parameter can be scored from 1 to 5, where 1 is the lowest and 5 the highest score based on the values of technical, commercial and environmental parameters according to look-up table for competitive score (Table 5) [1]. For instance, the score for technology with efficiency or DoD higher than 95% is 5 for the specific parameter. Also, the technology that has the longest life, or the lowest environmental impact can be scored with 5. Moreover, the score for the C-rate, depth of discharge, maturity of technology and environmental impact is an integer, fixed number, while the score for the other parameters is an interpolation between 1 to 5. The assignation of competitive scores to each storage technology is presented in Table 6, which is constructed by a mapping process between Table 4 (technology characteristics) and Table 5. In Appendix A is presented in detail the process that is followed to in order to get the competitive score of each technology for each parameter.

4.2.2 Assigning relevance weightings to parameters for applications

Some parameters of the storage technologies are more important than others, according to specific application. Thus, a set of weightings is applied to each parameter for several applications according to [1] and the sum of the weighting for each service should be equal to 100%. Table 7 presents an illustrative example of parameter weightings for each application.

Table 7: Parameter weighting for different applications

	Renewable shifting	**Renewable smoothing**	**Flex ramping**	**Ancillary services**	**Reactive power management**	**BTM power management**
Technical						
Efficiency	10%	10%	10%	10%	10%	10%
C-rate	0%	15%	0%	15%	0%	5%
DoD	15%	10%	15%	10%	10%	10%
Commercial						
Initial capital cost	25%	25%	25%	25%	25%	20%
Development & construction	5%	5%	5%	5%	5%	5%
Operating cost	15%	10%	15%	10%	10%	15%
Space required	5%	0%	5%	0%	15%	15%
Life	10%	10%	10%	10%	10%	5%
Maturity of technology	10%	10%	10%	10%	10%	10%
Environmental						
Environmental impact	5%	5%	5%	5%	5%	5%

Compared to [1], in this work the service of Transmission and Distribution (T&D) investment deferral is not included. The transmission network in Cyprus is very strong while for the distribution network we do not have relevant data to accurately score this type of service, and for these reasons it is ignored in this part of the analysis. Moreover, in [1] the environmental impact was not included and in this work its weighting it is defined for all the services to be 5%, while the weighting for the initial capital cost remains the highest but it is smaller compared to its value in [1]. Also, the weightings of depth of discharge and of operating cost are a bit higher in this work for the services of renewable shifting and flexible ramping because the PSoC is characterized by its high energy production from PVs during the noon each day and as a result these services operate every day, thus the operating cost is important. The energy which is charged or discharged to and from the energy storage technology, respectively, will be high and as a result the large usable capacity of the technology it is important because the PSoC is isolated and is not able to import and export energy to a neighboring power system.

4.2.3 Applying Suitability Matrix

The combination of the scoring for each technology and the weightings of each technology specific parameters according to their relevance for each application, indicates the suitability of each technology for each application. In order to avoid the complexity of this combination, an intermediate suitability matrix is used.

The scores of the suitability of each technology for each service is based on the previous results of Tables 6 and 7 and it was calculated as an interpolation from 0 to 1, where 0 means that the technology is not able to provide the service, while 1 means that is able to provide fully the service. For instance, the pumped hydro and the compressed air energy storages are not suitable for the BTM power management and their score is 0, while li-ion batteries are able to provide all the services. Table 8 shows the values of the suitability matrix.

Table 8: Suitability matrix for different applications

	Lead-acid battery	Mechanical storage			Lithium-ion batteries				High-temperature batteries		Flow batteries	
Parameters	**VRLA**	**Pumped Hydro**	**CAES**	**Flywheels**	**NMC**	**NCA**	**LFP**	**LTO**	**NaS**	**NaNiCI2 (Zebra)**	**ZBB**	**VRB**
Renewable shifting	0.75	0.5	1	0.25	1	1	1	1	1	1	1	1
Renewable smoothing	0.75	0.25	0.25	1	1	1	1	1	0.25	0.25	0.25	0.25
Flex ramping	0.75	0.5	1	0.25	1	1	1	1	1	1	1	1
Ancillary services	0.75	0.25	0.25	1	1	1	1	1	0.25	0.25	0.25	0.25
Reactive power management	0.25	0.25	0.25	0.5	1	1	1	0.75	0.25	0.25	0.25	0.25
BTM power management	0.5	0	0	0.25	1	1	1	1	0.5	0.5	0.5	0

For each service, two parameters have been selected in order to determine the suitability with some scenarios. For example, for renewable shifting the suitability score is 1 when the scores of operating cost and depth of discharge is greater than 3, while is equal to 0.75 when the operating cost score is greater than 3 and the DoD is smaller than 3. Also, for Pumped hydro the maximum score for suitability is 0.5 due to its impact to the environment. In

Appendix B, is presented in detail the methodology for assigning scores for the suitability matrix.

4.2.4 Application Ranking

With the multiplication of the competitive scores (Table 5), with the weighting values (Table 7) and suitability matrices (Table 8) from Steps 1 to 3, the weighted average competitive scores are calculated for each technology and each service, as shown in Table 9. Table 10 presents the ranking for the technologies with scores from 1 to 12, the most suitable for a specific application is ranked 1st and the least suitable is ranked 12th, based on their weighted average scores. Moreover, a coloured heatmap style was used for ease of identification of the most suitable technologies for each service (are shown with green), while the less suitable with red.

Table 9: Weighted average competitive score per ESS technology to perform a service type

	Lead-acid battery	Mechanical storage			Lithium-ion batteries				High-temperature batteries		Flow batteries	
Parameters	**VRLA**	**Pumped Hydro**	**CAES**	**Flywheels**	**NMC**	**NCA**	**LFP**	**LTO**	**NaS**	**NaNiCl2 (Zebra)**	**ZBB**	**VRB**
Renewable shifting	2.63	3.68	3.46	0.67	3.94	3.81	3.76	3.67	3.67	3.47	3.29	3.16
Renewable smoothing	2.92	0.88	0.83	3.06	4.09	3.86	3.93	3.82	0.88	0.83	0.77	0.74
Flex ramping	2.63	3.68	3.46	0.67	3.94	3.81	3.76	3.67	3.67	3.47	3.29	3.16
Ancillary services	2.92	0.88	0.83	3.06	4.09	3.86	3.93	3.82	0.88	0.83	0.77	0.74
Reactive power management	0.84	0.85	0.79	1.33	3.83	3.75	3.63	2.67	0.86	0.80	0.74	0.70
BTM power management	1.78	0	0	0.66	4.03	3.90	3.84	3.73	1.72	1.61	1.46	0

Table 10: Ranking of ESS technologies

	Lead-acid battery	Mechanical storage			Lithium-ion batteries				High-temperature batteries		Flow batteries	
Parameters	**VRLA**	**Pumped Hydro**	**CAES**	**Flywheels**	**NMC**	**NCA**	**LFP**	**LTO**	**NaS**	**NaNiCl2 (Zebra)**	**ZBB**	**VRB**
Renewable shifting	11	4	8	12	1	2	3	5	5	7	9	10
Renewable smoothing	6	7	9	5	1	3	2	4	7	9	11	12
Flex ramping	11	4	8	12	1	2	3	5	5	7	9	10
Ancillary services	6	7	9	5	1	3	2	4	7	9	11	12
Reactive power management	8	7	10	5	1	2	3	4	6	9	11	12
BTM power management	5	12	12	9	1	2	3	4	6	7	8	12

***Note: VRLA**: Valve-Regulated Lead Acid; **CAES**: Compressed Air Energy Storage; **NMC**: Nickel Manganese Cobalt; **NCA**: Nickel Cobalt Aluminium; **LFP**: Lithium Ferro Phosphate; **LTO**: Lithium Titanate Oxide; **NaS**: Sodium sulphur; **NaNiCl2**: Sodium nickel chloride; **ZBB**: Zinc Bromine Battery; **VRB**: Vanadium Redox Battery*

CHAPTER 5

THE CONCEPT OF SELF-CONSUMPTION OF SOLAR ENERGY

The self-consumption of solar energy is the economic model in which the building uses the electricity produced by the installed rooftop-PVs panels for its own electrical needs, thus acting as both producer and consumer, or prosumer. In this model, the PV-generated energy is consumed instantaneously as it is being produced or is stored in a battery energy storage system for use in later stage or is exported to the grid. The main advantages of self-consumption model are the greater economic benefits and better control of energy bills that it offers and that it promises greater independence from the grid.

5.1 Procedure for the model of self-consumption

In order to explain the procedure that is followed in the self-consumption model, there are two cases that are under examination. The first case is when the load demand is greater than the PV production which means that the prosumer imports energy from the grid and the battery is discharged, while the second case is when the load demand is smaller than the PV production and the prosumer exports energy to the grid and the battery is charged.

5.1.1 Calculation of the discharged energy of the battery

As regards the case when the load demand is greater than the PV production, initially is checked if the battery is empty or not. In the case that the battery is not empty and the difference between load demand and PV production (Load-PV) is greater or equal with the maximum discharge rate and if the stored energy of the battery is greater or equal with multiplication of maximum discharge rate and time difference between successive measurements (Δt), the battery is discharged by the value of this multiplication, while the battery will be fully discharged if the battery's stored energy is smaller than the maximum discharge rate multiplied by Δt. In the case that the battery is not empty and if (Load-PV) is smaller than the maximum discharge rate and (Load-PV) multiplied by Δt is smaller than the storage of the battery, the battery is discharged by this energy, while the battery will be fully discharged if (Load-PV) is smaller than the maximum discharge rate and (Load-PV) multiplied by Δt is greater than the stored energy of the battery. The following diagram (Figure 12) presents the procedure that is followed in the case that the load demand is greater than the PV production:

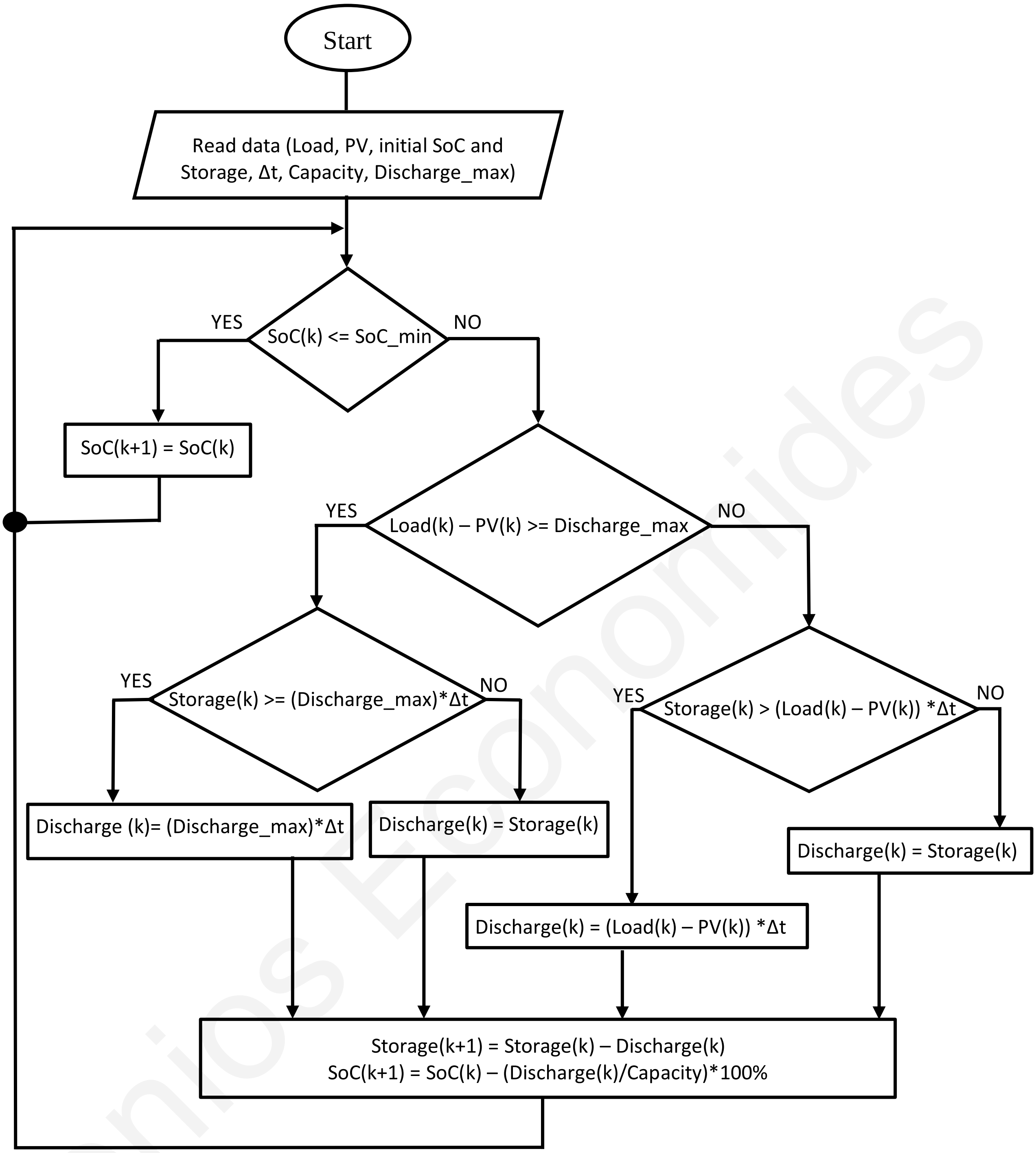


Figure 12: Procedure for self-consumption when load demand is greater than PV production

Note: ***Discharge*** is the discharged energy from the battery; ***Discharge_max*** is the maximum power discharge rate; ***k*** is the timestamp of data; ***Load*** is the load demand (W); ***PV*** is the energy production from rooftop-PVs panels (W); ***SoC*** is the battery's state of charge (%); ***Storage*** is the stored energy of the battery; ***Δt*** is the time difference between successive measurements

5.1.2 Calculation of the charged energy of the battery

Regarding the case when the load demand is smaller than the PV Production, the first step is to check if the battery is fully charged or not. In the case that the battery is not fully charged and the difference between PV production and load demand (PV – Load) is greater or equal with the maximum charge rate and if the difference between battery's capacity and battery's stored energy (Capacity – Storage) is greater or equal with maximum charge rate (Charge_max) multiplied by the time difference between successive measurements (Δt), the battery is charged by Charge_max, while if the difference is smaller than Charge_max, the battery is charged by this difference. In the case that the battery is not fully charged and if (PV – Load) is smaller than Charge_max and smaller than (Capacity – Storage), the battery is charged by the (PV – Load) multiplied by Δt, while the battery will be charged (Capacity – Storage). In the following diagram (Figure 13) the procedure that is followed in the case that PV production is greater than load demand is presented.

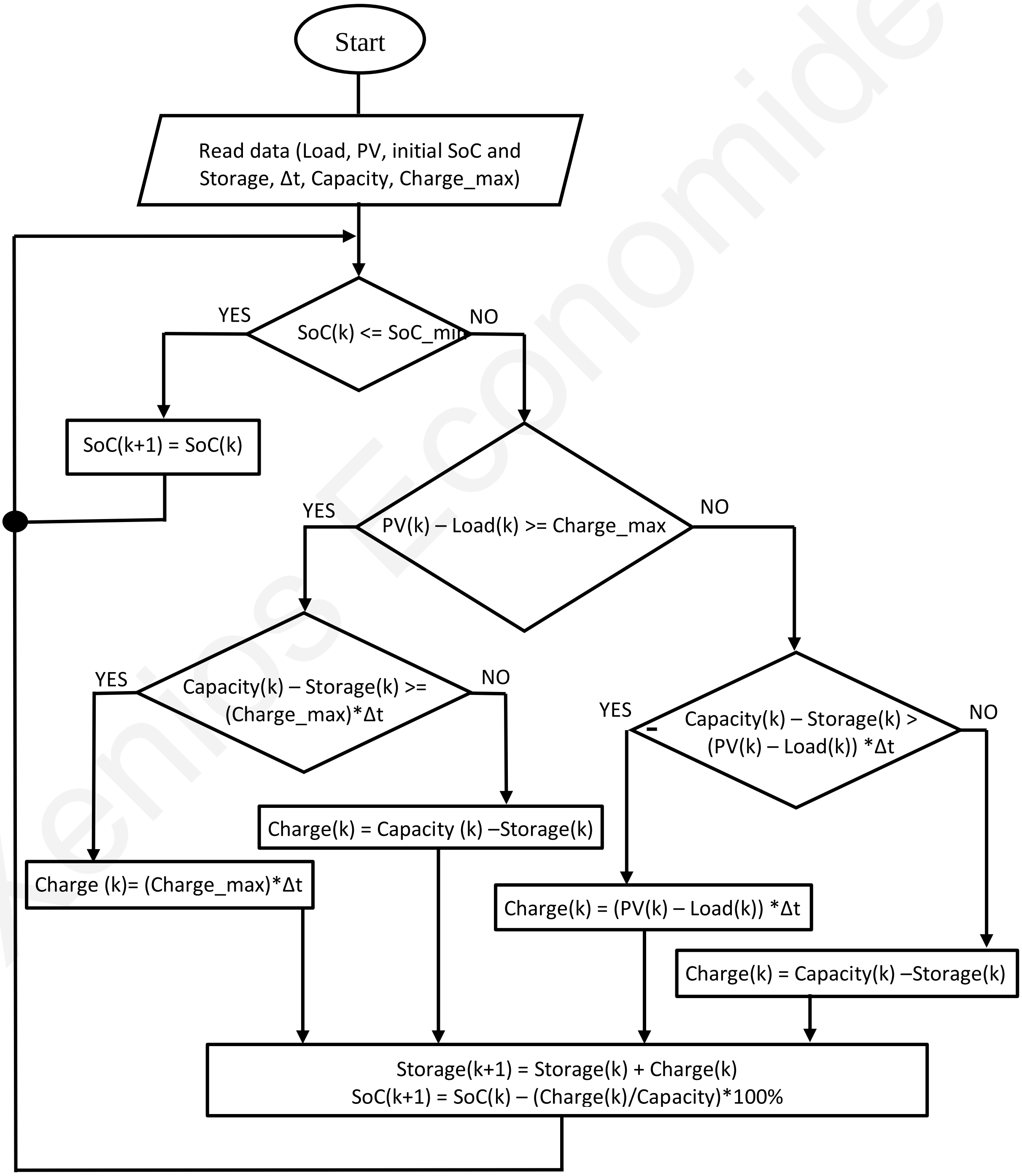


Figure 13: Procedure for self-consumption when PV production is greater than load demand

Note: ***Capacity*** is the capacity of the battery (energy); ***Charge*** is the charged energy to the battery; ***Charge_max*** is the maximum energy charge rate; ***k*** is the timestamp of data; ***Load*** is the load demand (energy); ***PV*** is the energy production from rooftop-PVs panels; ***Storage*** is the stored energy of the battery; ***Δt*** is the time difference between successive measurements

5.1.3 Calculation of imported energy from grid and exported energy to grid

As mentioned before, when the load demand of a prosumer is greater than the production of the roof-top PVs, the prosumer need to import energy from the grid, while if the load demand is smaller than the PV production, the prosumer exports energy to the grid.

In the case that the prosumer imports energy from the grid, the amount of the imported energy is the multiplication of the time difference between successive measurements and of the difference between load demand and PV production when the battery is empty. However, if the battery is not empty, the imported energy is the difference between load demand and PV production minus the stored energy of battery.

When the user exports energy to the grid, the exported energy is equal with the difference between PV production and load demand if the battery is fully charged. In the case that the battery is not fully charged, the exported energy is the PV production minus the sum of load demand and charged energy to the battery.

5.1.4 Self-consumption of a house with low load demand and high PV production

For the purposes of this work, a code was written in the software “Matlab” with which the self-consumption of a house is calculated during a year or for a specific period in a year. This calculation includes the amount of the imported and exported energy from and to the grid, respectively. In order to have the results, the load demand and the rooftop-PVs production are needed as inputs, as well as the characteristics of the battery which are the usable capacity and the maximum charge and discharge rate.

According to the procedure for self-consumption, which is described in the above sub-sections, Figures 14-17 presents data about the self-consumption of a prosumer with low load-demand and high PV production for a period of one week during four seasons: January; April; July and October. More specific, for each period in the Figure 14 the load consumption and PV production of the user is presented, the Figures 15 show battery’s state of charge and the Figures 16 present the charged and discharged energy to and from the battery, respectively and the imported energy from the grid and the exported energy to the grid, are shown in the Figures 17. Hence, the behavior of the model during different seasons regarding with the PV production, the stored energy in the battery, the imported and exported energy is investigated. The battery that is used in these calculations has 4.5 kilowatt-hours (kWh) usable capacity and maximum charge and discharge rate of 5 kilowatt (kW).

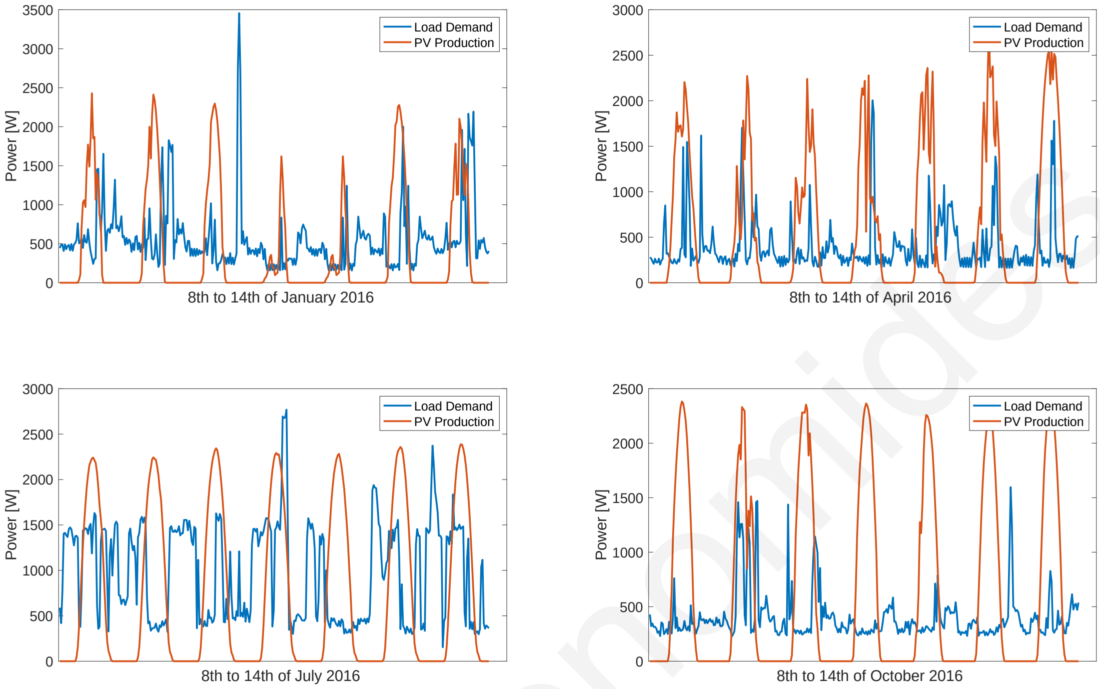


Figure 14: Load demand and PV production of the user for each period

According to the above graphs of the Figure 14, the load demand of the week in July is much higher compared to the other periods in the year, while the lower load demand is presented in the weeks of April and October. As regards the production from the rooftop PVs, the lower production is on the week of January, mainly due to the clouds in the sky and the low temperature during this period. The peak value of PV production during the other periods ranges around between 2.1 and 2.4 kW.

As shown in the below graphs of Figure 15, in January for two days in a row the battery was never fully charged because of the low production of rooftop-PVs during these days, while for the rest of the periods the battery was fully charged around noon, except one day in July because of the high load demand during this day. Moreover, during all these periods the fully charged battery was fully discharged before it was starting to be charged again. The discharged and charged energy is presented in detail for each period in the Figure 16.

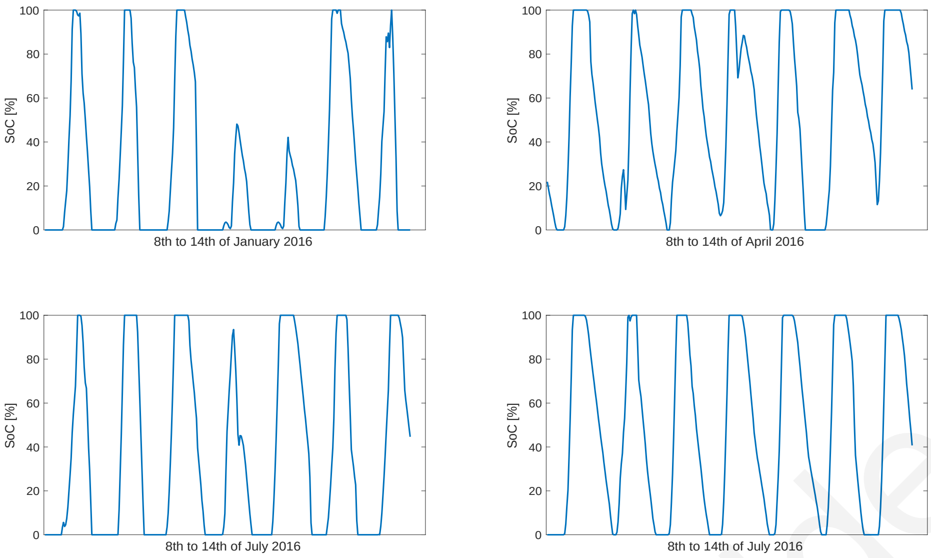


Figure 15: State of charge of battery of the user for each period

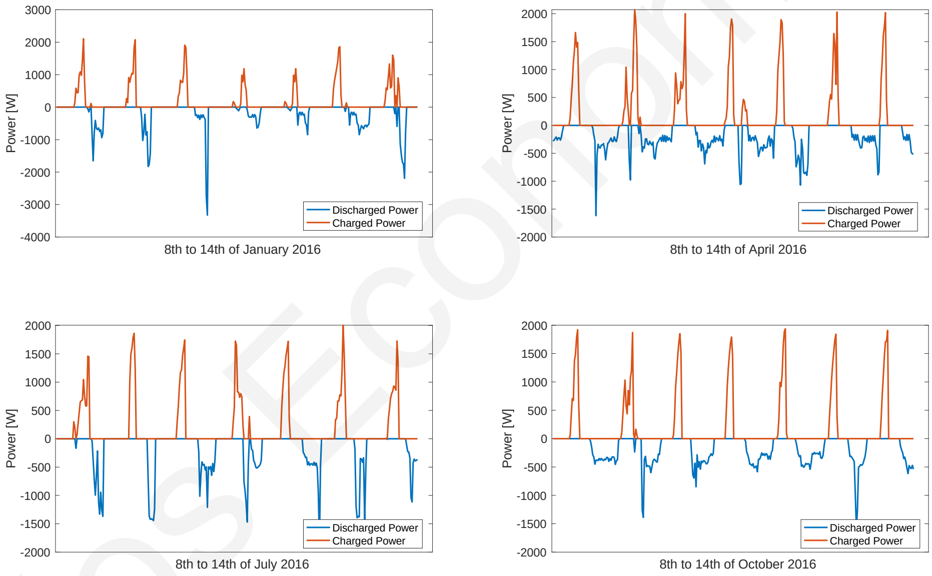


Figure 16: Discharged and charged energy of battery for each period

As a result, under self-consumption with installed battery the imported energy from the grid (Figure 17) is significantly reduced, up to 87% for a week and 64.3% for the whole year, compared to the case without installed battery. More specific, the Table 11 presents the decrease of the imported energy from the grid between the cases without and with installed battery.

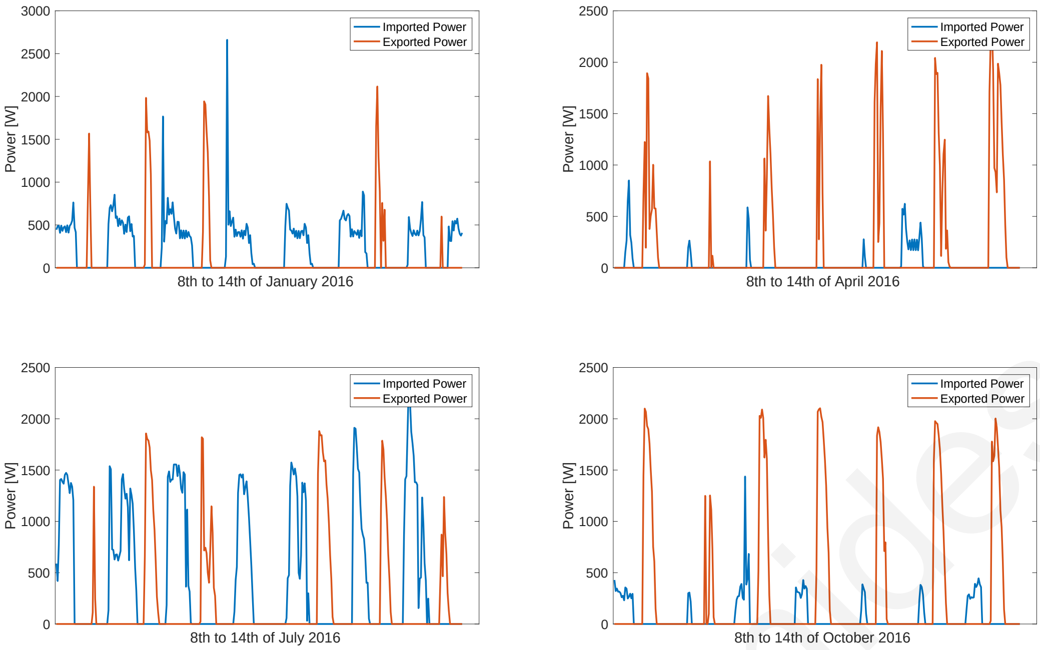


Figure 17: Imported from the grid and exported energy to the grid for each period

Table 11: The decrease of the imported energy by using the self-consumption model

	Imported Energy		
Period	**Without Battery**	**With Battery**	**Decrease (%)**
8th-14th of January	69.44	39.26	43.46
8th-14th of April	39.76	5.03	87.02
8th-14th of June	99.65	69.33	30.42
8th-14th of October	41.83	10.39	75.16
Whole year	5334	1904.4	64.29

CHAPTER 6

ECONOMIC ASSESSMENT OF BTM STORAGE

The goal of this economic assessment is to evaluate if the investment for the installation of energy storage system at a private premise will be profitable and if it is, what is the profit. The type of the installed ESS is lithium-ion batteries which is the most suitable for the case of PSoC as it is concluded in the Chapter 4. The consideration is on the impact on the total annual cost of different:

- capacity of the storage systems *(see the sub-section for the "Types of BESS for BTM applications for LV prosumers")*
- user's profile regarding the consumption and the production of each premise *(see the sub-section for the "Classification of Users' profile")*
- elecrticity billing schemes – *Net-Metering and Net-Billing schemes*
- year of the investment

In order to evaluate the economic assessment of the examined storage solutions, the Net Present Value (NPV) approach has been followed.

6.1 Classification of the network users at the low voltage side of the DSO

At the low voltage side of power system, there are costumers that either only buy energy (pure consumers) or customers of the electricity supply which buy energy but also produce energy from locally installed PVs (prosumers). The categories of the users according to their electricity scheme are presented as follows.

6.1.1 Costumers without installed PVs on a private house

In the case of a house without installed PVs, the user pays an amount for the electricity bill every 2 months which includes some variable and some fixed costs. The variable charges of the bill are based on the imported volume of energy (measured in kWh) for the house and include the energy charge, the network charge, the ancillary services charge, the fuel adjustment charge, RES and ES funds, while the fixed charges concern the meter reading and energy supply.

6.1.2 Customers with installed PVs and Net-Metering scheme

"***Net-Metering***" is defined as the method used for customers of the EAC who have installed a small PV system on the roofs of their premises or on the ground within the same plot with the premises, in order to meet the needs of the premises.

According to this method which counts for the difference between the electricity imported from the network to the customer substation to meet the needs of premises and the electricity produced by the PV system, which is exported to the network, for each pricing period (two months). Any surpluses will be transferred to the next pricing period, while any deficits will be normally priced by the EAC, within the specific pricing period (bill). In the last bill of the year, the existing surpluses are deleted. Any surpluses cannot be transferred from one-year offset to the next.

In the case that imported energy is greater than exported energy for a specific pricing period, the electricity bill of the consumer includes variable costs, which include the energy charge, the network charge, the ancillary services charge, the fuel adjustment charge, RES and ES funds. The cost of these charges is based on the value of the difference between the imported and the exported energy. Moreover, the customer pays some fixed costs, such as the producer's fee, Public Service Obligations (PSO) and RES and ES funds, and charges for meter reading and energy supply.

If the exported energy is greater than imported energy for a specific pricing period, the electricity bill of the customer includes variable and fixed costs. The variable cost is based on the difference between imported and exported energy and include the network charge and the ancillary services charge, while the fixed cost includes the charges for meter reading and energy supply.

6.1.3 Customers with installed PVs and Net-Billing scheme

"***Net-Billing***" is the method used to calculate the difference between the cost of purchasing electricity imported by the power system and credit from the sale price of the excess electricity produced from RES and exported to the network (according to the purchase price of Electricity from RES as determined by CERA) for each pricing period. The electricity bill of the user includes variable and fixed costs. The variable cost of the bill is based on the imported energy and consists of the energy charge, the network charge, the ancillary services charge, the fuel adjustment charge, RES and ES funds. On the other hand, the fixed cost includes the producer's fee, PSO, RES and ES funds and charges for meter reading and energy supply. The selling price is mainly sensitive to the fuel price. Moreover, a user with Net-Billing scheme can combine this scheme with energy storage system in order to store the excess energy and sell electricity when the storage system is fully charged. In this work is assumed that the use of Net-Billing scheme is starting from January of 2020 and the installation and the use of batteries in private premises are allowed from January 2020.

6.2 Input parameters for calculating the electricity bill

In order to calculate the electricity bill for the defined users, data regarding the tariffs for domestic use, the characteristics of the installed batteries in the case of Net-Billing scheme and the consumption and production of the users are necessary.

6.2.1 Tariffs for Domestic Use

Tariffs for domestic use are applicable where the electricity is solely used for domestic purposes to private dwellings. The initial tariffs that are used in this work are shown in Table 12 and their prices are according to data from EAC [27] for the reference year 2018.

In this work, two different prices for the fuel adjustment charge were analyzed: the first price concerns the first 6 months (January to June), while the second price is for the other 6 months (July to December) of the year. Each price is the average of the prices of the included months. For the energy purchase from RES under the Net-Billing scheme, the purchase price that is used is the average of purchase prices of the reference year 2018.

Table 12: Electricity tariffs for domestic consumers

Name	Price
Variable charges for imported energy	
Energy Charge per unit (kWh)	0.0923 € / kWh
Network Charge per unit (kWh)	0.0321 € / kWh
Ancillary Services Charge per unit (kWh)	0.0067 € / kWh
Fuel Adjustment charge per unit (kWh)	0.0158 € / kWh (January to June) 0.0421 € / kWh (July to December)
RES and ES Funds per unit (kWh)	0.0100 € / kWh
Total Variable charges per unit (kWh)	**0.1573-0.1842 € / kWh**
Selling price for exported energy	
Selling Price per unit (kWh)	**0.1042 € / kWh**
Constant charges	
Meter Reading Charge	0.98 €
Energy Supply Charge	4.68 €
Total Constant chargers	**5.66 €**

Notes: Variable charges are based on the imported energy; Purchase price for energy from RES is based on the exported energy for the case of Net-Billing scheme

6.2.2 Types of BESS for applications for LV prosumers

Three different BESS technologies, and their compatible inverters and accessories were investigated in order to calculate the savings on the electricity bills of prosumers under Net-Billing schemes. The most important characteristic of the energy storage system is the usable capacity of the batteries and then the inverter ratings. The assumed investment CAPEX of the BESS is based on tenders enquires. The characteristics of the batteries which are used in the analysis are showed in Table 13.

Table 13: Characteristics of BTM BESS for LV prosumers

Battery configuration	Inverter Rating (kW)	Rated Capacity (kWh)	Usable Capacity (kWh)	Warranty	Rated Cycles	Cost (€) without VAT
Inverter: Fronius 5.0 Battery: LG Chem 10H (+accessories)	5	9.8	9.3	10	6000	7550
Inverter: Fronius 5.0 Battery: LG Chem 7H (+accessories)	5	7	6.6	10	6000	6550
Inverter: Solttaro 1Φ Battery: Solttaro (LiFe04)	5	5	4.5	Inverter: 5 Battery: 10	10000	2960

6.2.3 Classification of users' profile

In order to calculate the savings on the electricity bill of the above schemes, a classification of 68 LV prosumers was performed based on their historical electricity consumption and production profiles for a whole year recorded every 30 minutes. The available data include measured imported and exported power, estimated power production from 3 kW PV system and their consumption. The classification process identified four categories of users which are: (1) the low consumption and production (L-L), (2) the low consumption and high production (L-H), (3) the high consumption and low production (H-L) and (4) the high consumption and high production (H-H).

First, the consumption and production for a whole year for all the users and then the average values of consumption and production were calculated. It is assumed that there are three descriptive features for the users' consumption and the production (low, medium, high). The users who have medium average consumption or production were ignored and the rest of the users were categorized. The annually consumption and production of the selected users is showing in the Table 14:

Table 14: Consumption and production for a whole year of the selected users

	L - L	L – H	H - L	H - H
Consumption (kWh)	4405	5334	8807	9550
Production (kWh)	4056	5408	4281	5512

6.3 Sensitivity Analysis

The sensitivity analysis, for the electricity cost and the savings obtained by prosumers under either Net Metering, Net-Billing or Net-Billing with battery includes four scenarios in which the tariffs for domestic use are changing based on the estimated value for the penetration of RESs in the power system of Cyprus and estimates of the electricity tariffs associated with the projections for the fuel price.

6.3.1 Examples of variables that can be tested

6.3.1.1 Variable charges of electricity bill

According to statistical data of the electricity prices for households in Cyprus [28] and those reported by the EAC for fossil fuel adjustments in the bill [29] for the period from 2014 to 2018, it can be noticed that these two parameters are directly correlated and follow the same pattern as shown in Figure 11 and 12.

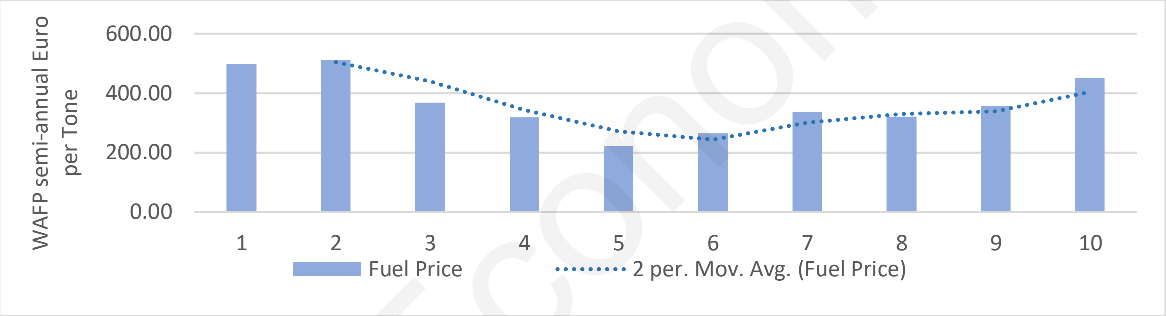


Figure 18: Semi-annual EAC weighted average fuel price (WAFP) evolution for 2014-2018 [29]

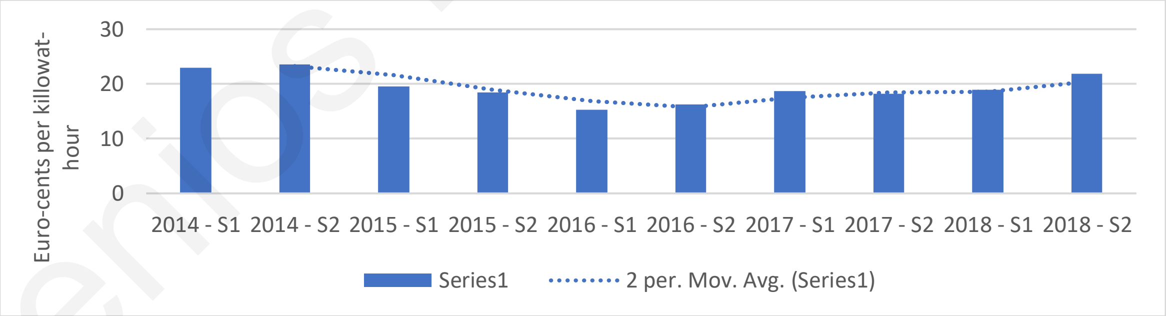


Figure 19: Semi-annual electricity price evolution for households in Cyprus 2014-2018 [28]

6.3.1.2 Fuel Adjustment charges

In order to calculate the total unit price (per kWh), the basic unit price of €300 per metric tonne of fuel is added to the Fuel Adjustment Cost, which arises from any increase or decrease in the cost of fuel.

6.3.1.3 *Purchase price for energy from RESs*

Figures 13 and 14 show that there is a direct correlation between the purchase price of energy from RESs [30] and the monthly weighted average fuel price for the electricity produced by conventional units of the EAC [29]. Specifically, this price is increasing when the fuel price is increasing, while it is decreasing when the fuel price is decreasing.

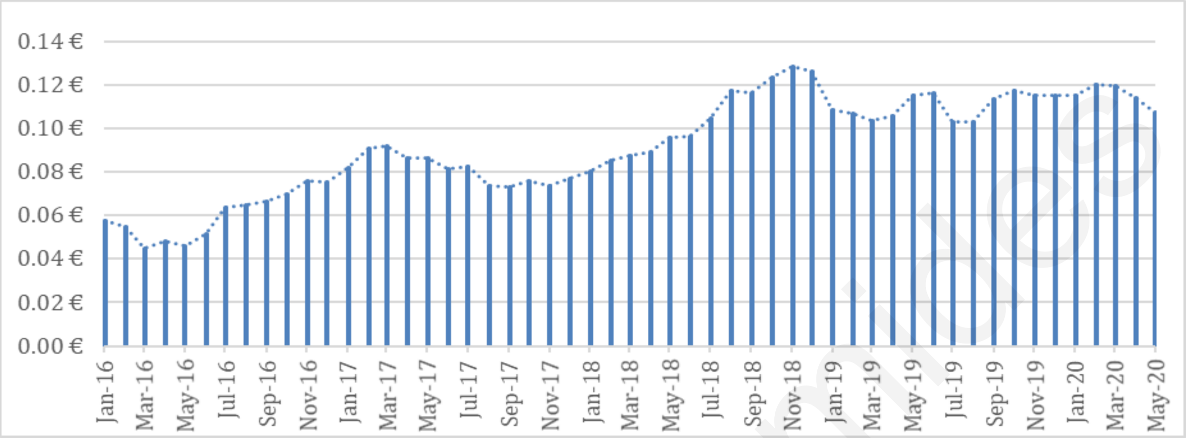


Figure 20: Purchase Price for energy from RESs [30]

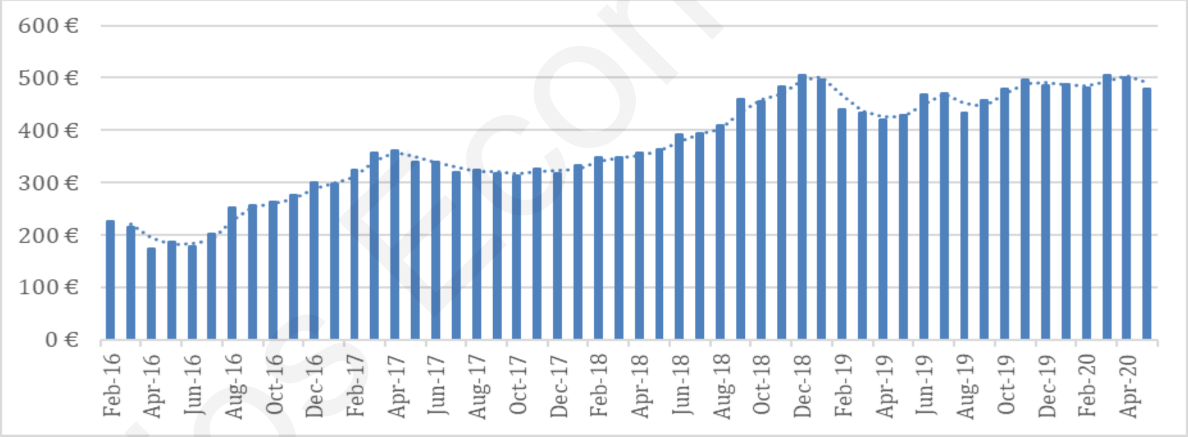


Figure 21: Monthly weighted average fuel price [29]

6.3.2 Scenarios in the Sensitivity Analysis

The sensitivity analysis includes four scenarios. The main parameters which have different values in each scenario are the total variable charges or the fuel adjustment charges of the imported energy and the selling price of the exported energy. In different scenarios, the value of these parameters is either increasing or decreasing according to the RES penetration into the PSoC and the price of gas oil and natural gas each year.

The correlation between the percentages of increasing in the value of the RES penetration and fuel price (gas oil and natural gas), which are used in this analysis are presented in Table 15 based on data of [31].

Table 13: Increasing of RES penetration and fuel price for the years from 2020 to 2030

Year	Increasing of RES Penetration (%)	Increasing of Gas Oil Price (%)	Increasing of Natural Gas Price (%)
2020	0	0	0
2021	0	0	0
2022	25.95	4.82	0
2023	4.52	6.30	4.88
2024	8.65	5.19	4.37
2025	3.10	4.17	3.81
2026	2.15	2.49	1.59
2027	1.26	2.21	1.46
2028	0	1.47	1.59
2029	14.52	2.26	1.58
2030	9.78	1.35	2.25

6.4 Net Present Value assessment of ESS at LV prosumers

The Net Present Value (NPV) is the method that estimates the potential change in an investor's wealth caused by the investigated project while the time value of money is being included. NPV equals the present value of net cash inflows generated by a project minus the initial investment on the project. In general, the NPV is used to assess the profitability of the investment.

In order to calculate the NPV, the monetized costs and benefits of the project must first be estimated using the same assumptions (e.g. real, constant year-of-study values). These costs and benefits are incurred at different times and are discounted to the time for which the assessment is needed (i.e. the year in which the study is performed) using a discount rate. Discounted costs (negatives) and benefits (positives) can then be compared in order to calculate the NPV of the project.

The analysis period starts with the commissioning date of the project and extends to a timeframe covering the economic life of the battery. The economic lifetime is the period for which the asset remains useful and for which it is prudent to calculate social benefits and costs.

6.4.1 Discount Rate

The discount rate considers the time value of money and the risk/uncertainty of anticipated future cash flows. The discount rate is very significant for assessing energy storage projects as costs are incurred predominately at the beginning of the project while the financial revenues of the installation are received only in the long-term. According to Article 19 (Discounting of cash flows) for the programming period 2014-2020 of the EU Commission Delegated Regulation (No 480/2014), the European Commission recommended that a 4% discount rate reflects a real reference parameter in the long term (EC, 2014). Considering this number, for the benchmark scenario of this study, the discount rate was taken to be 4%.

6.4.2 Time horizon of the techno-economic assessment

The time horizon of the techno-economic assessment was taken to be ten years, which is the useful economic life of the tested storage solution. The year of reference of the analysis is therefore the year 2020 that will be based on 2018 simulation data.

6.5 Results of the NPV calculations

In the following tables, the results of the NPV calculations for the scenarios are presented. The four scenarios are:

1. Increasing the Fuel Adjustment Charges for the imported energy and the Selling Price for the exported energy
2. Increasing the Variable Charges for the imported energy and the Selling Price for the exported energy
3. Decreasing the Variable Charges of the imported energy based on RES penetration and increasing Selling price
4. Decrease in 2022 for the Variable Charges for imported energy and then increasing them and the Selling Price for exported energy

Each scenario includes the Net-Metering and Net-Billing scheme. The initial investment for installing a photovoltaic system of 3 kW installed power in this research is assumed to be equal with 3500 euros (€) according to tenders which includes the PV panels, the inverter of the system and the cost for installing the system. As regards the Net-Metering scheme, the charges are variable depending on the imported energy. In the scenario with Net-Billing scheme, there are: the case without and the case with installed battery, while for the latter there are additional three cases based on the usable capacity of the installed battery (as described in the previous sub-section “Types of Batteries”). The case of Net-Billing scheme with installed battery includes two cases related to the year of investment in the energy storage system. In the case the investment will take place in the year 2022, in this research the cost of the storage system is assumed to be 10% less compared to the case of 2020. According to [32], the price of the lithium-ion batteries is expected that will be reduced about 25% in 2023 compared to the price in 2020. Here, is mentioned that the profits that are showed in the following tables are compared with the cost of electricity bills without installed roof-top photovoltaic systems.

6.5.1 Scenario 1: Increasing the Fuel Adjustment Charges for the imported energy and the Selling Price for the exported energy

The increase which is shown in this scenario for fuel adjustment charges and for selling price is based on the expected increasement of the price of the gas oil. More specific, the initial cost for the imported energy is values of fuel adjustment charges are 0.1569 €/kWh for the first half of the year (January to June) and 0.1832 €/kWh for the second half of the year (July to December), while the initial value of selling price is 0.1042 €/kWh. Thus, the increasement that is used in the calculations for the variable charges for imported energy and selling price for exported energy, is the following:

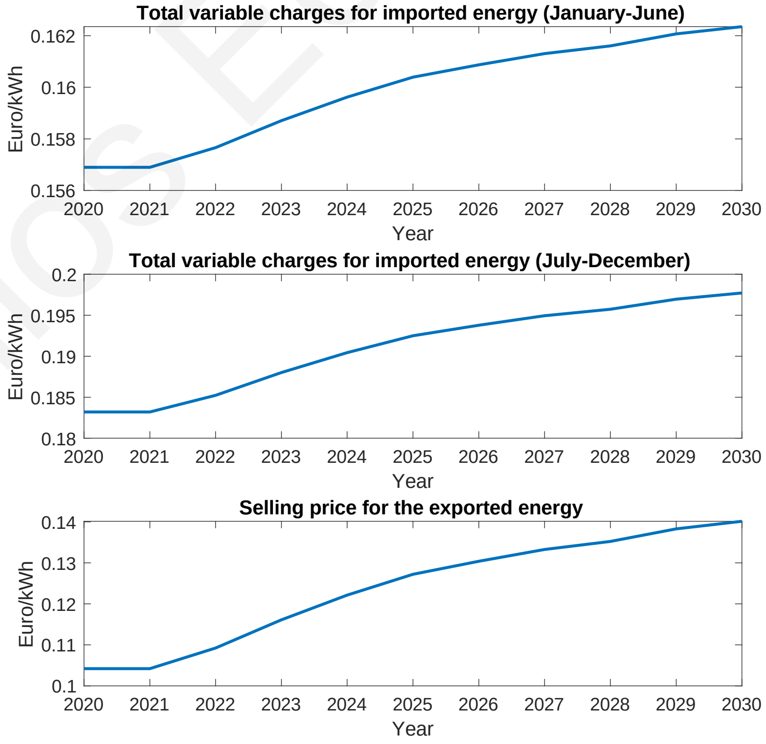


Figure 22: Total variable charges for imported energy and selling price for exported energy for Scenario 1

Table 14: NPV of Net-Metering and Net-Billing schemes without installed battery for Scenario 1

User	NPV for Net-Metering scheme (€)	NPV for Net-Billing scheme Without installed Battery (€)
Low Consumption Low Production	4076	2374
Low Consumption High Production	6096	4443
High Consumption Low Production	4306	3166
High Consumption High Production	6521	5170

Table 15: NPV of Net-Billing scheme wit installed battery and the pay-off time of the investment for Scenario 1

User		NPV for Net-Billing scheme with installed battery					
		in 2020			in 2022		
		Usable Capacity of Battery (kWh)					
		4.5	6.6	9.3	4.5	6.6	9.3
Low Consumption Low Production	Savings (€)	-247	-4328	-5414	221	-3168	-4069
	Pay-off year	--	--	--	2030	--	--
Low Consumption High Production	Savings (€)	1831	-2211	-3272	1812	-1058	-1936
	Pay-off year	2028	--	--	2028	--	--
High Consumption Low Production	Savings (€)	355	-3778	-4878	1272	-2586	-3499
	Pay-off year	2030	--	--	2028	--	--
High Consumption High Production	Savings (€)	2523	-1516	-2533	2994	-360	-1201
	Pay-off year	2027	--	--	2027	--	--

As per Scenario 1, it is shown in Table 16 that all the prosumers with Net-Metering scheme have more profits compared to prosumer with Net-Billing scheme. The users with Net-Metering have more profits because their variable charges include only the network charge and the ancillary services charge, while the prosumers under Net-Billing scheme pay for all the variable charges for the imported energy which is much higher than the selling price for exported energy. Moreover, Table 17 shows that installation of a battery with usable capacity 4.5 kWh is a good investment because it is paid-off until 2030 for all prosumers for both cases of the year that the battery will be installed, except the prosumer with low consumption and production who installed the battery in 2020. The paid-off period is earlier for the prosumers with high production compared to the users with low production. For the other batteries with greater usable capacity the investment is not paid-off until 2030, mainly because the price of these storages is much higher compared to the battery with the smallest usable capacity.

6.5.2 Scenario 2: Increasing the Variable Charges for the imported energy and the Selling Price for the exported energy

In scenario 2, the variable charges for imported energy, including as initial price of fuel adjustment charges the price 0.0421 €/kWh for the whole year, are increased according the increasement in the price of the gas oil, while in Scenario 1 only the fuel adjustment charges are increased as regards the price of the imported energy. The increase of selling price in this scenario is the same as the case in Scenario 1, where this price is increased based on the increasement in the price of the gas oil, too. The values which are used in the calculations for both parameters, variable charges for imported energy and selling price for exported energy, are the following:

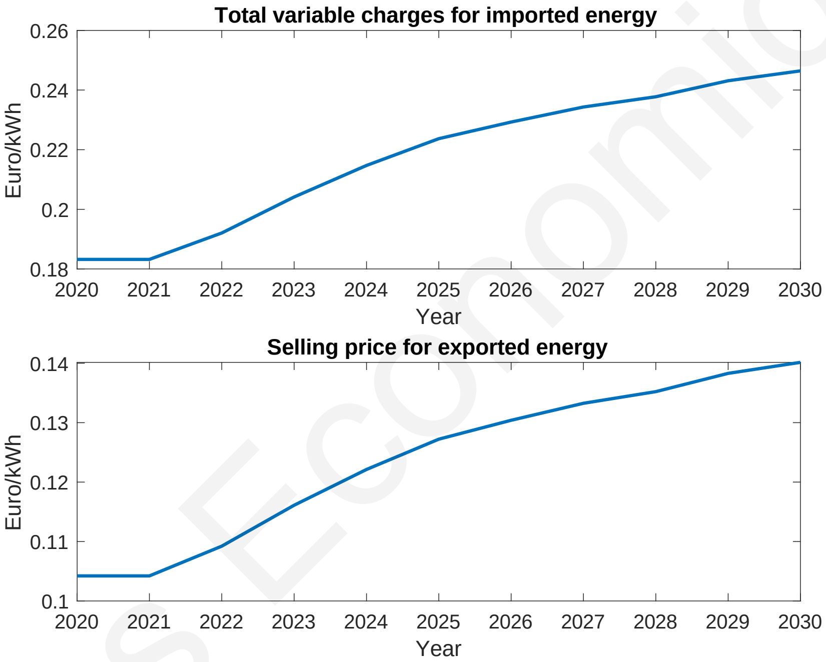


Figure 23: Total variable charges for imported energy and selling price for exported energy for Scenario 2

Table 16: NPV of Net-Metering & Net-Billing schemes without/with installed battery for Scenario 2

User	NPV for Net-Metering scheme (€)	NPV for Net-Billing scheme Without installed Battery (€)
Low Consumption Low Production	5685	3027
Low Consumption High Production	8054	5312
High Consumption Low Production	6121	4111
High Consumption High Production	8835	6496

Table 17: Pay-off time of the investment of Scenario 2

User		NPV for Net-Billing scheme with installed battery					
		in 2020			in 2022		
		Usable Capacity of Battery (kWh)					
		4.5	6.6	9.3	4.5	6.6	9.3
Low Consumption Low Production	Savings (€)	1080	-2870	-3885	1524	-1739	-2571
	Pay-off year	2029	--	--	2028	--	--
Low Consumption High Production	Savings (€)	3387	-491	-1463	3328	631	-161
	Pay-off year	2027	--	--	2027	2030	--
High Consumption Low Production	Savings (€)	1855	-2162	-3186	2779	-995	-1835
	Pay-off year	2028	--	--	2027	--	--
High Consumption High Production	Savings (€)	4518	678	-181	4965	1801	1111
	Pay-off year	2026	2030	--	2026	2029	2029

The results of the Scenario 2 are presented in Tables 18 and 19. The profits for the prosumers under Net-Metering scheme in this scenario are also greater than in Net-Billing scheme because of the type of charges that the users pay under each scheme. Moreover, here it is noticed that installation of the available batteries is paid-off until 2029 in both cases regarding with the year for installing the battery for all the prosumers with battery of usable capacity 4.5 kWh. In the case of the user with high consumption and production the investment is paid-off in 2026, while the investment of the user with low consumption is paid-off in 2029. For the other batteries only the investment of the user with high consumption and production is paid-off until 2030, except the case of installed battery in 2020 with usable capacity 9.3 kWh. In this Scenario the savings are more than the profits in Scenario 1 and as a result the investment is paid-off a bit earlier. This happens due to the variable charges in Scenario 2 have higher cost (Figure 23) compared to the variable charges in Scenario 1 (Figure 22) and as the amount of imported energy is reduced, the profits are increasing.

6.5.3 Scenario 3: Decreasing the Variable Charges of the imported energy based on RES penetration and increasing Selling price

As regards the third scenario, the variable charges for the imported energy are decreasing based on the expected increasement of RES penetration in the power system of Cyprus, the variable charges are decreasing as the RES penetration is increasing. However, the selling price of the exported energy is increasing according to increasement that will be presented in the price of the gas oil.

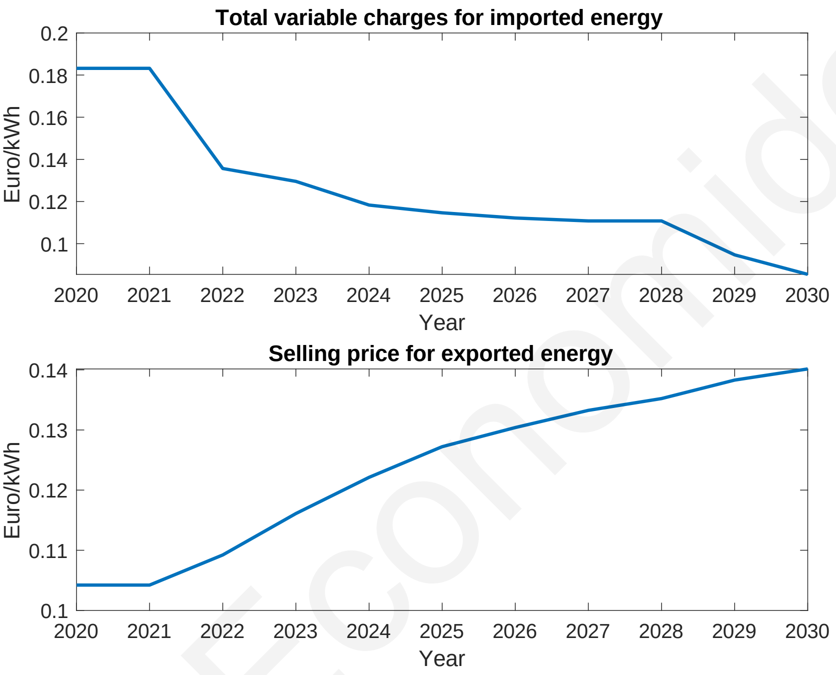


Figure 24: Total variable charges for imported energy and selling price for exported energy for Scenario 3

Table 18: NPV of Net-Metering & Net-Billing schemes without/with installed battery for Scenario 3

User	NPV for Net-Metering scheme (€)	NPV for Net-Billing scheme Without installed Battery (€)
Low Consumption Low Production	2056	1962
Low Consumption High Production	3480	3722
High Consumption Low Production	2290	2305
High Consumption High Production	3798	3830

Table 19: Pay-off time of the investment of Scenario 3

User		NPV for Net-Billing scheme with installed battery					
		in 2020			in 2022		
		Usable Capacity of Battery (kWh)					
		4.5	6.6	9.3	4.5	6.6	9.3
Low Consumption Low Production	Savings (€)	-1443	-5696	-6873	-1000	-4565	-5559
	Pay-off year	--	--	--	--	--	--
Low Consumption High Production	Savings (€)	317	-3928	-5104	258	-2806	-3802
	Pay-off year	2030	--	--	2030	--	--
High Consumption Low Production	Savings (€)	-1124	-5380	-6569	-199	-4213	-5208
	Pay-off year	--	--	--	--	--	--
High Consumption High Production	Savings (€)	421	-3824	-4988	868	-2700	-3696
	Pay-off year	2030	--	--	2029	--	--

In Scenario 3, the profits for prosumers with Net-Metering scheme and with Net-Billing scheme without installed energy storage (Table 18) do not differ significant due to the decrease of the variable charges for the imported energy. Also, in scenario 3 the investment becomes profitable only for the case of the prosumers with high PV production with an installed battery with usable capacity 4.5 kWh which is paid-off between 2029 and 2030. The investment for the batteries with larger capacity is not paid-off mainly because their capacity is not useful when the battery is combined with small PV system and their prices are higher than the price of battery with usable capacity 4.5 kWh.

6.5.4 Scenario 4: Decrease in 2022 for the Variable Charges for imported energy and then increasing them and the Selling Price for exported energy

In the fourth scenario, the total price of the variable charges for the imported energy decreases in 2022 because it is expected that almost all conventional units will operate with natural gas which has a lower price compared to gas oil and heavy fuel oil which were used by the end of 2021. This decrease is about 37% and is based on the difference of the price of gas oil from the price of natural gas and is very important. From 2022 to 2030 these charges are increasing according to the increasing of the price of the natural gas every year. The selling price for the exported energy is increasing every year based on the price of the natural gas.

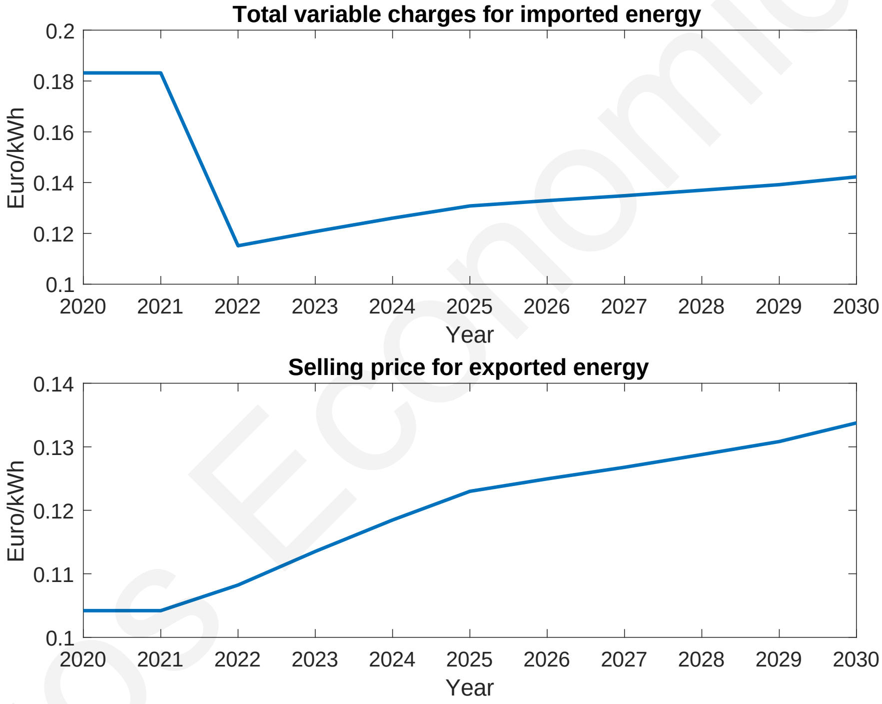


Figure 25: Total variable charges for imported energy and selling price for exported energy for Scenario 4

Table 20: NPV of Net-Metering & Net-Billing schemes without/with installed battery for Scenario 4

User	NPV for Net-Metering scheme (€)	NPV for Net-Billing scheme Without installed Battery (€)
Low Consumption Low Production	2596	2011
Low Consumption High Production	4159	3820
High Consumption Low Production	2860	2502
High Consumption High Production	4632	4209

Table 21: Pay-off time of the investment of Scenario 4

User		NPV for Net-Billing scheme with installed battery					
		in 2020			in 2022		
		Usable Capacity of Battery (kWh)					
		4.5	6.6	9.3	4.5	6.6	9.3
Low Consumption Low Production	Savings (€)	-1117	-5896	-7043	-673	-4765	-5728
	Pay-off year	--	--	--	--	--	--
Low Consumption High Production	Savings (€)	698	-4188	-5325	639	-3066	-4023
	Pay-off year	2029	--	--	2029	--	--
High Consumption Low Production	Savings (€)	-718	-6101	-7249	207	-4934	-5898
	Pay-off year	--	--	--	2030	--	--
High Consumption High Production	Savings (€)	1073	-4462	-5569	1520	-3338	-4277
	Pay-off year	2029	--	--	2028	--	--

In Scenario 4, there is not significant difference in profits for prosumers with Net-Metering scheme and with Net-Billing scheme without installed energy storage (Table 20). The main reason of this small difference in the profits of these two cases is the reduction of the variable charges for the imported energy. Hence, as smaller are these charges, the profits are reducing. Moreover, in this scenario the investment becomes profitable only for the case of the prosumers with high PV production with an installed battery with usable capacity 4.5 kWh which is paid-off between 2028 and 2029 and for the case of a prosumer with high consumption and low production with installed battery in 2022 with usable capacity of 4.5 kWh. The investment for the other batteries is not paid-off, mainly for the reasons that their large usable capacity is not useful when they are combined with small PV system and their prices are much higher compared to the battery with usable capacity 4.5 kWh.

CHAPTER 7

CONCLUSION

In this work, a techno-economic analysis of energy storage system technologies suitable for the power system of Cyprus, following the current design of the electricity market, was done. Initially, various energy storage technologies which were examined in this research were ranked according to their technical, economic and environmental parameters based on the case of Cyprus. From the ranking methodology for suitable energy storage technology, it was concluded that the Li-Ion battery energy storage systems are the most suitable in order to provide a set of services either at grid level or at low voltage distribution power grid. Here is mentioned that generally the pumped hydro storage is an attractive storage technology but because of environmental constraints of Cyprus in this study is ranked lower than Li-Ion batteries.

Then, the concept of self-consumption combined with energy storage system was investigated. More specific, a user is able to store produced energy from PVs in a storage system and use it in later time. In this study, a prosumer with low load-demand, high PV production and a battery with capacity of 4.5 kWh was under examination for one week during four seasons in order to investigate the amount of the imported energy from the grid. The results show that the imported energy is significantly decreased compared to the case without installed battery.

Finally, a techno-economic assessment investigates the low voltage distributed storage units by using the Net Present Value (NPV) approach for available Li-Ion battery energy storage systems. From the results of this analysis is showed that the investment of a low-voltage prosumer under Net-Billing scheme for installing a storage system will be profitable earlier if the investment takes place in 2022 than in 2020 because the cost of the battery storage system is estimated to be reduced and the difference between the savings before the installation and the savings with installed battery for this period is not significant. Also, it is noted that the in the case that the usable capacity of the battery is the smallest (4.5 kWh), the investment is paid-off until 2030 mainly for the users with high PV production in all scenarios of this study. This happens because the battery with usable capacity 4.5 kWh has the cheapest price and also the larger capacity of the other batteries is not useful when they are combined with small PV system of installed power 3 kW. Moreover, it is observed that in the case of Net-billing scheme with installed battery, the savings are significantly lower compared to the case of Net-billing without installed battery. Generally, the savings from Net-Metering scheme currently are higher compared to the savings under Net-Billing scheme. However, in the future it may be necessary the installation of energy storage system at private premises for the consumers in order to be allowed the installation of PV system for addressing some challenges of the power system, such us the high PV production during noon where the energy may be curtailed because the generators in power plants cannot reduce the production under a limit because they are able to operate until a specific level.

The characteristics of energy storage system technologies are constantly being improved. Hence, in the future a new ranking could be made for new storage technologies in order to have an updated version of the ranking. Also, the data of the users that are used in this work includes production from roof-top PVs of 3kW installed power. Therefore, it will be very interesting to use data of prosumers with larger installed power of PVs and examine how it affects the amount of imported energy from the grid and the year that the investment for installing energy storage system at low voltage side will be profitable. Finally, the sensitivity analysis of economic assessment could be extended to include additional parameters which affects the electricity price.

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APPENDICES

Appendix A: Methodology for assigning competitive scores. The results are based on the parameters of Table 5

1. Efficiency:

```
If efficiency > 95 %
    Then efficiency_score = 5
Elseif efficiency > 86.25 % and efficiency =< 95 %
    Then efficiency_score = 4 – 4.9
Elseif efficiency > 77.5 % and efficiency =< 86.25 %
    Then efficiency_score = 3 – 3.9
Elseif efficiency > 68.75 % and efficiency =< 77.5 %
    Then efficiency_score = 2 – 2.9
Elseif efficiency >= 60 % and efficiency =< 68.75 %
    Then efficiency_score = 1.1 – 1.9
Elseif efficiency < 60 %
    Then efficiency_score = 1
```

2. C-rate:

```
If C_max > 1C
    Then C _score = 5
Elseif C_max > C/2 and C_max =< 1C
    Then C _score = 4
Elseif C_max > C/4 and C_max =< C/2
    Then C _score = 3
Elseif C_max > C/8 and C_max =< C/4
    Then C _score = 2
Elseif C_max =< C/8
    Then C _score = 1
```

3. Depth of Discharge (DoD):

```
If DoD > 95 %
    Then DoD_score = 5
Elseif DoD > 86.25 % and DoD <= 95 %
    Then DoD_score = 4
Elseif DoD > 77.5 % and DoD <= 86.25 %
    Then DoD_score = 3
Elseif DoD > 86.25 % and DoD <=<77.5 %
    Then DoD_score = 2
Elseif DoD =< 60 %
    Then DoD_score = 1
```

4. Initial capital cost (ICC):

```
ICC = Storage Capex + PCS Capex)
If ICC < 500 €/kWh
    Then ICC _score = 5
Elseif ICC > 500 €/kWh and ICC <= 850 €/kWh
    Then ICC _score = 4 – 4.9
Elseif ICC > 850 €/kWh and ICC <= 1200 €/kWh
    Then ICC _score = 3 – 3.9
Elseif ICC > 1200 €/kWh and ICC <= 1550 €/kWh
    Then ICC _score = 2 – 2.9
Elseif ICC > 1550 €/kWh
    Then ICC _score = 1
```

5. Development and Construction (D&C):

```
If D&C <= 6 months
    Then D&C_score = 5
Elseif D&C > 6 months and D&C =< 16.5 months
    Then D&C_score = 4 – 4.9
Elseif D&C > 16.5 months and D&C =< 27 months
    Then D&C_score = 3 – 3.9
Elseif D&C > 27 months and D&C =< 37.5 months
    Then D&C_score = 2 – 2.9
Elseif D&C > 37.5 months and D&C =< 48 months
    Then D&C_score = 1 – 1.9
Elseif D&C > 48 months
    Then D&C_score = 1
```

6. Operating cost (OC):

Lowest OC of all technologies = 5
Highest OC of all technologies = 1

For the rest technologies the score is an interpolation between 1 to 5
Range_OC = OC_max – OC_min (e.g. 74 – 0.9 = 73.1)
Range_Score = Score_max – Score_min (e.g. 5-1 = 4)
Score_step = 0.1 (e.g 1, 1.1, 1.2,…, 4.8, 4.9, 5)
OC_step = Range_OC / (Range_Score * Score_step) (e.g. (73/4) * 0.1) = 1.8)
(e.g. Score=5 → OC = 0.9 €/kWh, Score = 4.9 → OC = 0.9 + OC_step = 2.7 €/kWh)

7. Space required:

```
If Space > 500 Wh/kg
    Then Space _score = 5
Elseif Space <= 500 Wh/kg and Space > 382.5 Wh/kg
    Then Space _score = 4 – 4.9
Elseif Space <= 382.5 Wh/kg and Space > 265 Wh/kg
    Then Space _score = 3 – 3.9
Elseif Space <= 265 Wh/kg and Space > 147.5 Wh/kg
    Then Space _score = 2 – 2.9
Elseif Space <= 147.5 Wh/kg and Space > 30Wh/kg
    Then Space _score = 1 – 1.9
Elseif Space < 30 Wh/kg
    Then Space _score = 1
```

8. Life:

Longest Life of all technologies = 5
Shortest Life of all technologies = 1

For the rest technologies the score is an interpolation between 1 to 5
Range_Cycles = Cycles_max – Cycles_min (e.g. 15000 – 1000 = 14000)
Range_Score = Score_max – Score_min (e.g. 5-1 = 4)
Score_step = 0.1 (e.g. 1, 1.1, 1.2,…, 4.8, 4.9, 5)
Cycles_step = Range_Cycles / (Range_Score * Score_step) (e.g. (14000/4) *0.1) = 350)
(e.g. Score=1→ Life= 1000 cycles, Score=1.1→ Life= 1000 + Cycles_step = 1350 cycles)

9. Maturity of technology:

```
If Maturity = Mature
    Then Maturity _score = 5
Elseif Maturity = Commercialisation
    Then Maturity _score = 4
Elseif Maturity = Early Commercialisation
    Then Maturity _score = 3
Elseif Maturity = Demonstration
    Then Maturity _score = 2
Elseif Maturity = Prototype
    Then Maturity _score = 1
```

10. Environmental impact (EI):

EI=Human_health + Human_toxicity + Particulate_matter + Fossil_resource + Ecosystems

Lowest environmental impact of all technologies = 5
Pumbed Hydro is not suitable for the case of Cyprus due to its high impact in ecosystem and has the highest environmental impact of all technologies = 1

For the rest technologies the score is a fix number between 2 to 4 according

```
If EI = Low
    Then EI _score = 4
Elseif EI = Medium
    Then EI _score = 3
Elseif EI = High
    Then EI _score = 2
```

Appendix B: Methodology for assigning scores for the suitability matrix. The results are based on the data of Table 6

- **Storage (j,i),** where ***j*** corresponds to the type of storage technology, and ***i*** is the parameter of the storage technology (technical, commercial and environmental)
- **Service (k,j),** where ***k*** is the service type, and ***j*** is the type of storage technology

Genaral: 0 <= score_Service <= 1

```
If technology is able to provide fully the service
     Then score_Service = 1
Elseif technology is able to provide the service
     Then score_Service= 0.75
Elseif technology is able to provide partially the service
     Then score_Service= 0.5
Elseif technology is able to provide poorly the service
     Then score_Service= 0.25
Elseif technology is not able to provide the service
     Then score_Service = 0
```

1. Renewable Shifting (RSh):

```
If OC_score = 1 and DoD_score = 1
   Then RSh_score = 0
Elseif OC_score = 1
   Then RSh_score = 0.25
Elseif OC_score <= 3
   Then RSh_score = 0.50
Elseif OC_score > 3 and DoD_score < 3
   Then RSh_score = 0.75
Elseif OC_score > 3 and DoD_score =>3
   Then RSh_score = 1
```

2. Renewable Smoothing (RSm):

```
If C_score = 1
   Then RSm_score = 0
Elseif C_score < 3
   Then RSm_score = 0.25
Elseif C_score < 4 and DoD_score <= 3
   Then RSm_score = 0.50
Elseif C_score <= 5 and DoD_score <= 3
   Then RSm_score = 0.75
Elseif C_score <= 5 and DoD_score > 3
   Then RSm_score = 1
```

3. Flex Ramping (FR):

```
If OC_score = 1 and DoD_score = 1
   Then RSh_score = 0
Elseif OC_score = 1
   Then RSh_score = 0.25
Elseif OC_score <= 3
   Then RSh_score = 0.50
Elseif OC_score > 3 and DoD_score < 3
   Then RSh_score = 0.75
Elseif OC_score > 3 and DoD_score =>3
   Then RSh_score = 1
End
```

4. Ancillary Services (AS):

```
If C_score = 1
   Then AS_score = 0
Elseif C_score < 3
   Then AS_score = 0.25
Elseif C_score < 4 and DoD_score <= 3
   Then AS_score = 0.50
Elseif C_score <= 5 and DoD_score <= 3
   Then AS_score = 0.75
Elseif C_score <= 5 and DoD_score > 3
   Then AS_score = 1
End
```

5. Reactive Power Management (RPM):

```
If Space_score = 1 and ICC_score = 1
   Then RPM_score = 0
Elseif Space_score <= 2
   Then RPM_score = 0.25
Elseif ICC_score <=2.5
    Then RPM_score = 0.50
Elseif Space_score <= 5 and ICC_score <= 4
    Then RPM_score = 0.75
Elseif Space_score <=5 and ICC_score > 4
    Then RPM_score = 1
```

6. BTM Power Management (BTMPM):

```
If Space_score = 1
   Then BTMPM_score = 0
Elseif Space_score <= 2.5 and OC_score <= 3
   Then BTMPM _score = 0.25
Elseif Space_score <= 2.5 and OC_score > 3
    Then BTMPM _score = 0.50
Elseif Space_score > 2.5 and OC_score < 4
    Then BTMPM _score = 0.75
Elseif Space_score > 2.5 and OC_score >=4
    Then BTMPM _score = 1
```