IMPROVED SELF-CONSUMPTION IN RESIDENTIAL BUILDINGS USING COUPLED PV-BES SYSTEMS

by

Stavros Afxentis

Submitted to the University of Cyprus in partial fulfilment of the requirements for the degree of Master of Science in Electrical Engineering

Department of Electrical and Computer Engineering

March 2023

IMPROVED SELF-CONSUMPTION IN RESIDENTIAL BUILDINGS USING COUPLED PV-BES SYSTEMS

by

Stavros Afxentis

Examination committee:

Georghiou E. George
Professor, Department of Electrical and Computer Engineering, Advisor

Ellinas Georgios
Professor, Department of Electrical and Computer Engineering

Charalambous A. Charalambos
Associate Professor, Department of Electrical and Computer Engineering

Abstract

Environmental concerns about fossil fuel resources for electricity generation lead towards the integration of renewable energy sources (RES) into the modern power grid. Solar photovoltaics is the most widely used technology at the time. Despite the volatile nature of photovoltaics (PV), governments around the world encourage the integration of PV systems into the electricity network, especially for residential use. The financial incentives and governmental subsidies, along with the increasing electricity prices over the last years, resulted to the dramatic increase of residential PV systems. Furthermore, grid parity conditions combined with favourable policies for promoting PV technology such as the net-metering and feed-in tariffs, have promoted PV technology towards achieving the national energy targets.

Considering the isolated electricity network of Cyprus, the unobstructed deployment of distributed PV generation brings many challenges to the forefront that are mainly associated with the quality of the network, such as voltage and frequency fluctuations in areas with dense PV systems. In addition, the intermittent generation of PV systems due to clouds could cause voltage deviations that can compromise the stability of the network.

The adoption of energy management strategies to control the flow of PV generation is a popular solution for mitigating those issues. One approach is to use battery energy storage (BES) systems. This requires optimal sizing of the battery energy storage for local energy storage or dispatch to the low voltage (LV) grid according to load and price responsive control mechanisms to promote the storage of surplus energy for later use. For instance, the network congestion can be reduced by using the local BES system to manage peak load demand and excess PV generation. In light of this, a proper battery scheduling strategy and an appropriate BES sizing are important aspects towards building a suitable environment for residential use of BES systems.

The purpose of this master’s thesis is to analyze the energy profile of residential prosumers with a PV system in Cyprus and develop a procedure for optimally sizing the BES system in a PV-BES coupled residential system, opting to maximize the self-consumption ratio (SCR). The proposed BES sizing methodology is benchmarked with data from four residential PV-BES pilot systems installed in Nicosia, Cyprus.

Acknowledgments

I would like to express the deepest appreciation towards my supervisor Prof. George E. Georghiou for the valuable and persistent advice he has offered me, and for giving me the opportunity to undertake such an exciting project.

Furthermore, I would like to thank my friends and family for their continuous support and compassion all the time.

I am also deeply grateful to Dr. Michalis Florides and Dr. Spyros Theocharides for their useful guidance and assistance in this project.

Finally, I would like to thank the PV Technology Lab staff for their support throughout my studies at the University of Cyprus.

Table of Contents

Table of Figures

List of Tables

Nomenclature

AC	Alternating Current
BES	Battery Energy Storage
BTM	Behind-the-Meter
CC	Charge Controller
DC	Direct Current
DG	Distributed Generation
DR	Demand Response
DSM	Demand Side Management
DSO	Distribution System Operator
EMS	Energy Management System
ESS	Energy Storage System
FiT	Feed-in Tariff
FTM	Front-of-the-Meter
IRQ	Interquartile Region
LiFePO4	Lithium-Iron Phosphate
LV	Low Voltage
MPPT	Maximum Power Point Tracking
PF	Power Factor
PV	Photovoltaics
RES	Renewable Energy Sources
SCR	Self-Consumption Ratio
SM	Smart Meter
SoC	State of Charge
THD	Total Harmonic Distortion
TZ	Target Zero method
UCY	University of Cyprus
WSS	Within-Cluster sum of squares

1. Introduction

1.1.Background and Motivation

A few years back, energy storage technology was not considered a priority for improving the power systems performance and flexibility. This is because of the large-scale and centralized fossil fuel-based system for energy generation and because energy storage technology was not a well developed and economically feasible technology. However, the urgent need for power system decarbonization, mainly through renewable energy sources (RES), keeps improving the cost-performance of energy storage technology [1].

The European Union has set ambitious energy and climate policies to be achieved by 2030 including a 32% target for RES energy consumption and 32.5% for energy efficiency. Even higher energy goals have been set on a long term, targeting 55% in the gross final energy consumption by 2050. The share of RES in electricity consumption could rise to 64% in a high energy efficiency scenario and 97% if energy storage technologies are incorporated to accommodate the intermittent RES supply [2]. This implies a substantial energy system transformation, allowing increased RES deployment and at the same time maintain the quality, efficiency and competitiveness of the energy system. In response to the above obstacles, Europe has set the long-anticipated energy package-[3], that promotes the industrialization and competitiveness in the renewable energy sector across the European Union and proposes the transformation of passive consumers to active prosumers (i.e., to be engaged as producers and consumers). The Communication on Accelerating Clean Energy Innovation [4] makes specific reference on the development of energy storage technologies as one of the four priorities for research and innovation areas. Considering this, substantial transformation from a centralized energy system to a distributed green energy network is expected within the next years. The increased share of RES and Distributed Generation (DG) for electricity generation will be challenging in terms of power system quality and sustainability, however the benefits of flexible energy storage solutions can assist dramatically towards achieving the energy package targets. More specifically, the growth of RES integration in the energy system will introduce fluctuating and intermittent power streams due to the uncertainty of renewables. This can bring difficulties for the system operators to keep the energy system stable and secure. Fast response and flexible resources for ancillary services should be accommodated to prevent unexpected incident in the network, whilst maintaining stability and quality.

Energy Storage Systems (ESS) is a flexible and reliable solution that can be used for the modernization of the existing energy system and can bring adequate reliability to achieve the desired energy targets. Different technologies for storing energy have been introduced and tested such as pumped-storage hydropower, compressed air energy storage and thermal storage which have shown considerable development and integration with RES [5], [6]. Nevertheless, only a few storage technologies are suitable as the transformation of the existing energy system requires high technical and performance specifications. For instance, pumped-storage hydropower is a mature and well-established technology for energy storage, but its development is strictly limited by geographical and ecological constrains whereas the cost-performance is improved for large-scale systems only. More recent storage technologies such as electrochemical batteries have been introduced which are used for maintaining grid voltage and frequency within the acceptable operating levels. A commonly used electrochemical storage technology is the secondary (rechargeable) battery system since its fast response, long lifetime and compact size are vital for the energy system transformation. Energy storage can be integrated in the transmission and distribution network, commonly referred as in Front-of-the-Meter storage (FTM) or on the customer side known as Behind-the-Meter storage (BTM). For instance, FTM storage can provide ancillary grid services for maintaining grid stability and improving system flexibility. On the other hand, BTM offers attractive services to the customers that can increase their interest for investing in RES and also improves the cost performance of energy storage. Yet, the absence of suitable policy frameworks to incentivise storage deployment and services, leave battery technology as an expensive solution at the moment.

Even though the introduction of energy storage in the power system seems to be an ideal solution for achieving further RES penetration in the energy generation, significant investments are needed for the deployment of low-carbon technologies. Apart from large-scale investment on RES deployment, the power system modernization requires considerable research and development progress to lift off the barriers for energy storage deployment such as safety hazards, quality of supply and cost-performance. Nevertheless, energy storage technology is considered to play a crucial role in the transition to a low-carbon energy system by improving the efficiency, higher energy use, and promoting new regulatory frameworks that can support energy storage in terms of financial support and user remuneration [7].

1.2. Thesis Objectives

Energy storage and, especially rechargeable battery technology, is expected to play a key role in the transition to a low-carbon energy system. This thesis gives particular emphasis on the coupling of battery energy storage technology with residential PV (PV-BES) systems. The local storage of surplus PV generation can maximize the self-consumed electricity as a measure to reduce the LV distribution network congestion and grid issues caused by increased DG penetration levels. Relating these with the current situation in Cyprus, BES technology is still at its infancy and technological improvement is required before it becomes a reliable and acceptable storage solution. This work proposes a methodology for proper BES system sizing to improve the PV self-consumed yield and minimize the threads imposed under high PV penetration circumstances.

Towards this direction, this study examines the integration of BTM storage in residential premises with existing PV systems, attempting to maximize the self-consumption ratio (SCR) and reducing the energy needs of residential users from the grid. The main objectives are:

1. Analyze the load profiles and seasonal variation of residential buildings.
2. Develop a clustering analysis of prosumers based on daily import energy.
3. Develop a sizing methodology for residential PV-BES systems.
4. Provide the minimum design parameters for residential PV-BES systems.
5. Examine the performance of PV-BES systems installed in residential premises.

1.3. Novelty

The energy profiles of a large group of residential prosumers with PV systems in Cyprus were collected and analyzed to gain insight about the load profiles and seasonal diversity of the energy consumption. Daily grid exchange electricity such as import and export levels were used to develop a sizing methodology for residential BTM storage systems. BTM storage systems were installed as pilot systems to a small group of residential prosumers, forming the first commendable attempt towards integrating BES technology in the LV distribution grid of Cyprus.

2. Theoretical Background

2.1. Renewable Energy Sources in Cyprus

The non-interconnected power system in Cyprus is considered the primary barrier towards achieving high RES uptake and numerous technical and economical issues are to be considered. Until now, the electricity generation in Cyprus is predominantly based on fossil fuels and mainly crude oil, with the bulk of the electricity generation being provided by three main power stations with total installed capacity of 1.5GW.

Renewable generation was first introduced to the Cypriot energy market over the last decade and was primarily promoted through generous governmental subsidies and more recently through significant price drop. According to the statistics published by the Transmission System Operator of Cyprus, a stunning share of 88.3% of the total electricity generation is covered by fossil fuels. The remaining share of 11.74% comes from RES generation. By the end of 2020, 398.7MW wind parks have been installed with a contribution of 5.04% into the power system [8]. Photovoltaic (PV) contributed a 5.8% share, where the remaining 0.9% resulted from biomass power plants. The RES penetration levels have reached a considerable increase by 3.2% by the end of 2021, accounting to a combined share of 14.9% with 487.4MW of total installed RES systems. The RES penetration levels and installed capacity are illustrated in Figure 1 and Figure 2 respectively, from 2011 to the end of 2021. Wind parks amounted an average 5% on the total RES penetration, however the total installed capacity remains flat at 157.5MW over the last decade. The same stands for Biomass plants with a total installed capacity of 12.1MW and a constant penetration level of 0.8% on the annual electricity demand. The rest of the RES share increase over the last couple of years is mainly due to the exponential growth of PV installations, predominantly on the distribution network. More specifically, PV reached a share of 9.2% by the end of 2021 and a total installed system capacity of 317.8MW, achieving a 38.7% increase in comparison to 2019 values. This is a positive step towards energy sustainability, however this will give rise to grid issues that will be exacerbated by the small isolated electricity network of Cyprus, if no mitigation actions take place.

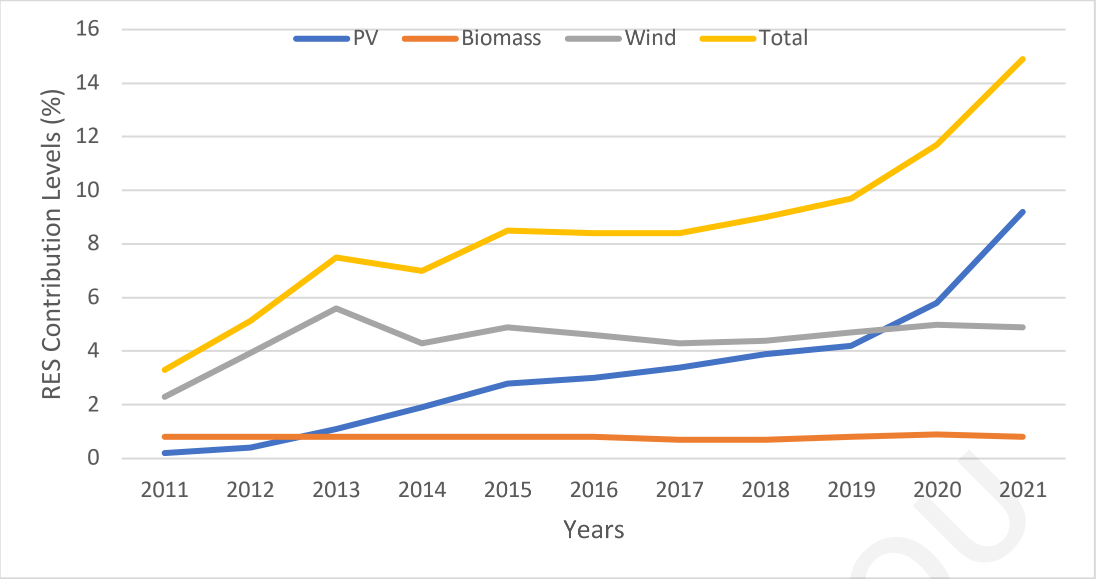


Figure 1. *Annual RES share in Cyprus, 2011-2021. The share was calculated based on the electricity demand in Cyprus.*

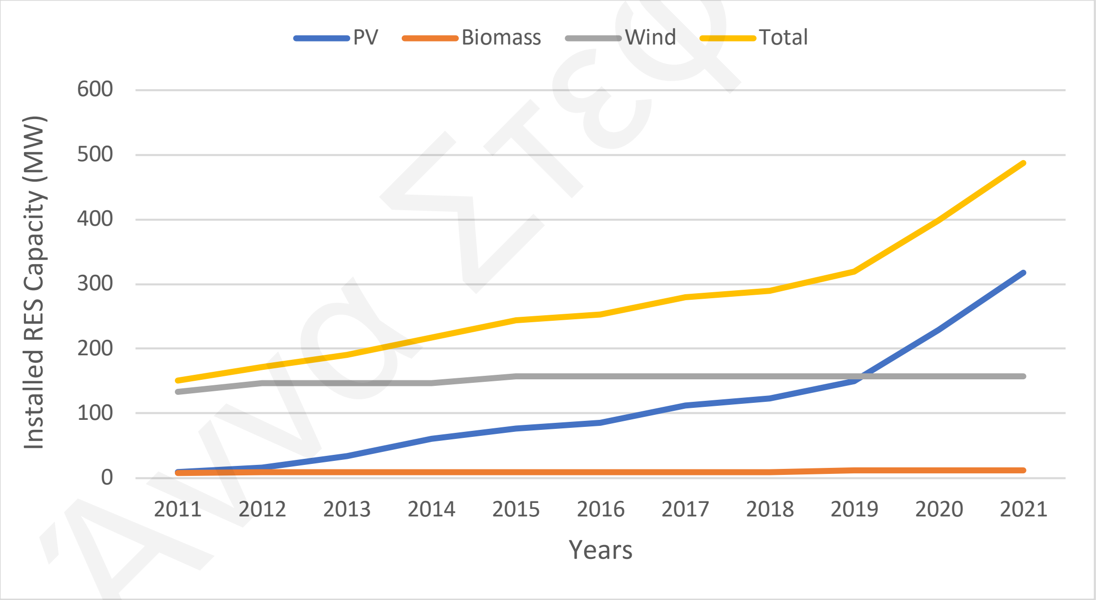


Figure 2. *Annual total installed RES capacity in Cyprus, 2011-2021.*

2.1.1. Energy Framework Review

Photovoltaic technology has seen remarkable growth in Cyprus during the last few years, with the PV installed capacity exponentially increasing over the years. The reason behind this is the significant cost decrease, within the range of 530 to 1600 €/kWp depending on the PV system size, that significantly reduced the levelized cost of electricity of PV systems across the European Union by 2021 [9]. This, along with attractive policy frameworks, have contributed to this significant increase of PV system installations in Cyprus. More specifically, the first support scheme was launched in 2010 by the Cyprus Government offering the Feed-in Tariff (FiT) remuneration for the PV generated electricity injected to the national grid. The support scheme covered incentives for small-scale PV systems up to 20kWp on commercial buildings. A similar scheme was also released in the same year as a bidding scheme to support large-scale PV projects having a capacity larger than 150kWp and a total cap of 50MWp.

In addition to this, the Net-metering support scheme was firstly established in 2013 which promoted the installation of residential PV systems with a maximum capacity of 3kWp. A framework amendment in 2015 increased the upper limit of Net-metering PV systems to 5kWp for three-phase systems. The most recent framework release in December 2021, increased the maximum PV installed capacity to 4.16kWp for single-phase residential buildings and up to 10.4kWp for three-phase residential buildings [10]. Later, the policy framework introduced the Net-billing scheme which promotes the installation of residential and commercial PV systems with maximum capacity up to 8MWp, with a system capacity limit being set at 80% of the annual load demand. Under the Net-billing scheme, the prosumer is reimbursed with an avoidance energy price for each surplus energy unit that is fed back to the network, compared to the Net-metering scheme where electricity purchasing and selling prices are equal. The Net-billing scheme also encourages self-consumption, paving the way towards optimal binding between PV and energy storage technologies, thus encouraging the transition of passive end-users to active “prosumers”. More specifically, the scheme allows the installation of energy storage systems to increase the self-consumed electricity, however the energy storage system is not allowed to interact with the network.

Despite the governmental attempts to promote self-consumption, the absence of incentive frameworks and the high price tag on energy storage systems, have not yet resulted in any storage uptake. The establishment of the right policy frameworks is a key element of the government’s strategic energy plan in order to further increase RES penetration. Achieving increased or even maximum self-consumption can be considered as a plan to optimally allocate storage in the future energy system and achieve system flexibility and transition.

2.1.2. Challenges of high RES impact

The urgent need for increased RES share in the energy mix, has led PV systems to exponentially increase over the last years. By the end of 2021, there was a notable increase of the installed PV capacity compared to the 2016 levels with many PV systems being integrated to the Low Voltage (LV) distribution network. Within the next decade, it is expected that RES growth will continue, exceeding the 30% share on the annual electricity demand. However, this poses many challenges on the network depending on the point of interconnection of PV systems and the state of the existing LV network elements.

The intermittent nature of RES, poses significant constrains especially under high PV penetration levels. A sudden change in solar irradiation (i.e., due to unexpected cloud movement) could lead to fast and considerable change in the PV output within a few seconds. The missing energy gap should then be covered from the bulk power generation units which also need to regulate frequency and voltage variations caused by the power flow intermittency [11],[12]. More specifically, the speed, frequency, voltage levels as well as the desired power of conventional power units need to be adjusted to cover any unexpected production loss from RES, thus increasing the operational expenses (i.e., more frequent maintenance costs, fuel cost) and decreasing the reliability of the power system. Furthermore, the reverse power flow in the distribution grid due to RES is another challenge. This occurs because RES production can get very high at some points in time, exceeding the load demand levels, allowing reverse power to flow towards the distribution grid leading to a higher voltage at the end of the feeders. A recent issue occurred in a high concentrating PV area of Cyprus with many LV-connected PV systems being disconnected by the DSO for a short period of time to maintain grid stability [13]. The development of new energy control strategies is urgently needed to cope with these challenges and mitigate the impact of intermittent RES nature.

Several methods have been proposed in literature to mitigate the impact of RES intermittency such as the minimum power import relays and reverse power flow relays. The former is a relay device designed to disconnect a grid-tied PV system when the generation falls below a certain threshold value or above the actual load demand [14], where the latter is designed to disconnect the PV system when the load demand falls to zero or when reverse power flow is detected. More effective methods have been proposed recently, such as the smart inverters which can regulate their output power and also support grid stability by providing voltage and frequency regulation, dynamic Volt-VAR/Watt control and output ramping [15].

Besides the technological developments, Demand Side Management (DSM) is a strategic concept which targets to optimally improve the demand behaviour of end-users. More specifically, DSM encourages users to alter their electricity use pattern. It is in turn a concept where load demand responds to monetary incentives to encourage users to buy energy-efficient devices or shift their demand response (DR) in off-peak times of demand [16]. In other words, DR implies a load shifting to times where the power system congestion is low. Further to this, the integration of energy storage with renewable sources is a new technological achievement which aims in maximizing the self-consumption from renewables and at the same time mitigate the grid quality issues stemming from RES. The business models of energy storage change depending on the point of network connection. The two major storage categories are FTM and BTM storage, offering significant services on the power gird [17]. For instance, FTM storage offers ancillary grid services such as voltage and frequency regulation and spinning reserve which are important for maintaining and improving the stability and reliability of the power system. Additionally, fast response ESS such as battery systems can support the integration of renewables by storing energy for later use. However, BTM storage offers a large and attractive number of services to the end-user which increases the customer interest and improves the cost performance of energy storage technology [18]. Additional services can be offered in the case of PV connected to the LV network, especially under high PV concentration conditions within a feeder. More specifically, the coupling of BTM storage with PV systems can bring important benefits to prosumer, such as the flexibility to self-consumption, minimize electricity cost via real-time or Time-of-Use tariff management and optimally manage the energy based on PV generation and load patterns [19]–[21]. Finally, grid stability including maintaining voltage and frequency levels within the acceptable ranges, can be achieved as the distributed BTM storage can balance the intermittent nature of RES.

For the purposes of this study, BTM storage topology is considered. The distributed and coordinated BTM storage provides significant flexibility and at the same time offers unique services to the power grid. Paving towards establishing a more reliable energy framework including remuneration for ancillary services and storing energy, the cost performance of BTM storage can be improved, thus encouraging users towards this direction.

2.2.Residential PV-BES Systems

Typical residential buildings in Cyprus have rooftop PV systems with capacity between 3kWp for single-phase (1-ph) systems and up to 5kWp for three-phase (3-ph) systems with an annual energy yield of 4800kWh and 8000kWh respectively. On the other hand, the annual expected energy consumption for a 1-ph household is 5000kWh whilst for a 3-ph household is 8000kWh. This situation renders the Net-Metering a favorable and cost-effective option over Net-Billing for residential PV systems since there is balance between consumed and produced electricity. However, the primary drawback of this scenario is that a large part of the PV generation does not coincide the load demand profile. Therefore, a large amount of the PV generated energy is being injected to the distribution grid which serves as a virtual energy storage unit. Conversely, load peaks occur when the PV production is low. This situation leads to a very low self-consumption ratio and has a substantial impact on the electricity network since the LV distribution network losses are increased. By introducing an energy storage system that is coupled to the existing PV system, surplus PV electricity can be stored locally and be used later when load demand is high, therefore improving the quality and efficiency of the power system [22]–[24].

The optimal design of residential energy storage systems coupled with PV requires careful dimensioning of both power and capacity to maintain high system performance, whilst keeping the system cost at minimum. Extensive analysis is required to optimally size the storage systems and is investigated in the next chapter of this work. In this section, the most practical system topologies for combining PV with energy storage systems are presented and the minimum design parameters when designing a PV system coupled to energy storage system are stated. The study considers lithium-ion based battery units as the energy storage system since the technological improvement of this technology over the past years can provide fast response charging and discharging power, high energy capacity as well as longer life-cycle when compared to other battery technologies [25]–[27]. The system topologies and the parameters provided next were used to select BES pilot systems for residential users with an existing PV system.

2.2.1. System Topology

Two commonly used topologies were identified in the market that can combine PV and BES systems (hereinafter mentioned as PV-BES system). These are the AC-Coupled and the DC-Coupled system configurations and can be identified from the connection point of the BES system. Considering that PV and BES systems are both DC sources, the AC-Coupled configuration uses a separate inverter (DC/AC) for each system to couple PV and BES to a common AC-bus which is connected to the domestic load and the LV distribution grid [28]–[30]. The system topology is shown in Figure 3 and includes a typical residential PV converter which consists of a DC-DC converter operating as the solar Maximum Power Point Tracking unit (MPPT), and a grid-connected inverter. On the storage side, a bidirectional battery converter is used and consists of a Charge Controller (CC) unit and a gird inverter [5],[31]. The DC-Coupled system topology is shown in Figure 4. It is formed by using a single power converter called “hybrid” converter which couples the PV and the Battery systems on a common DC-bus. The “hybrid” converter uses a DC/DC converter operating as the solar MPPT system and an extra DC/DC converter operating as the battery CC unit [32]. A common bidirectional on/off grid inverter is used for connection to the grid and domestic load.

In both topologies, a bidirectional energy meter is used for measuring the imported and exported energy to the grid. An Energy Management System (EMS) is embedded to control the operation of the PV and BES systems. More specifically, the EMS establishes communication with the solar PV converter and the BES system and retrieves information about the PV energy yield, BES charging/discharging state and State of Charge (SoC) as well as import and export electricity from the energy meter to perform suitable decisions for regulating the power flow towards the battery system and the distribution grid. By comparing the two topologies, the main advantage of the AC-Coupled system is that it can be easily coupled to an existing PV system without the need to replace the existing PV converter. Also, it is easy to expand the storage side by adding more converters if needed, to increase the storage capacity and power. On the DC-Coupled system, the same can be achieved by replacing the entire “hybrid” converter. However, the lower efficiency compared to the “hybrid” converter, make the DC-Coupled solution more suitable when it comes to system performance. A comparison between the two topologies is shown in Table 1.

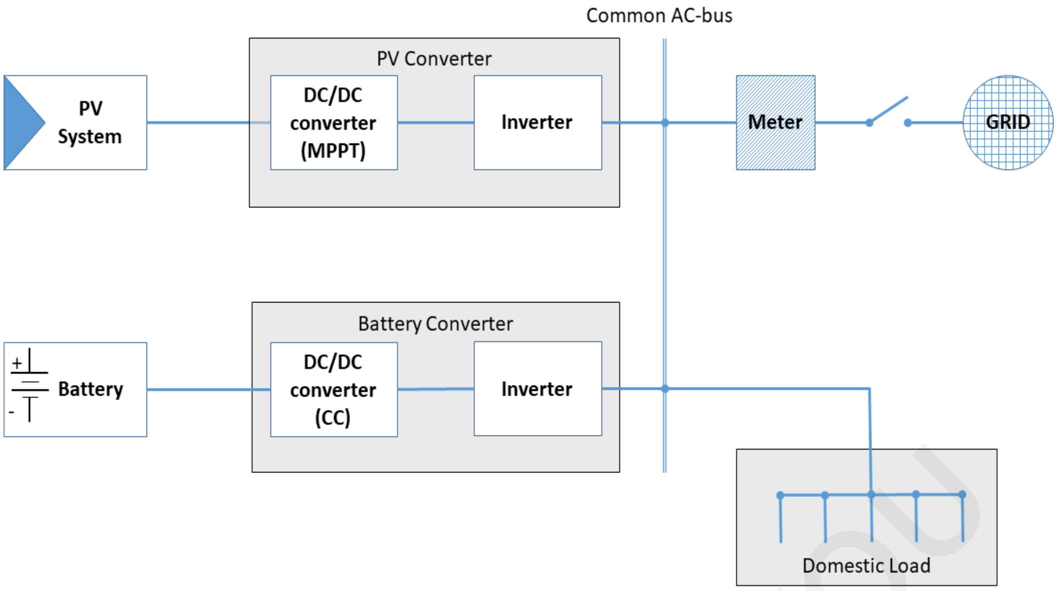


Figure 3. *Schematic diagram for the AC-Coupled system.*

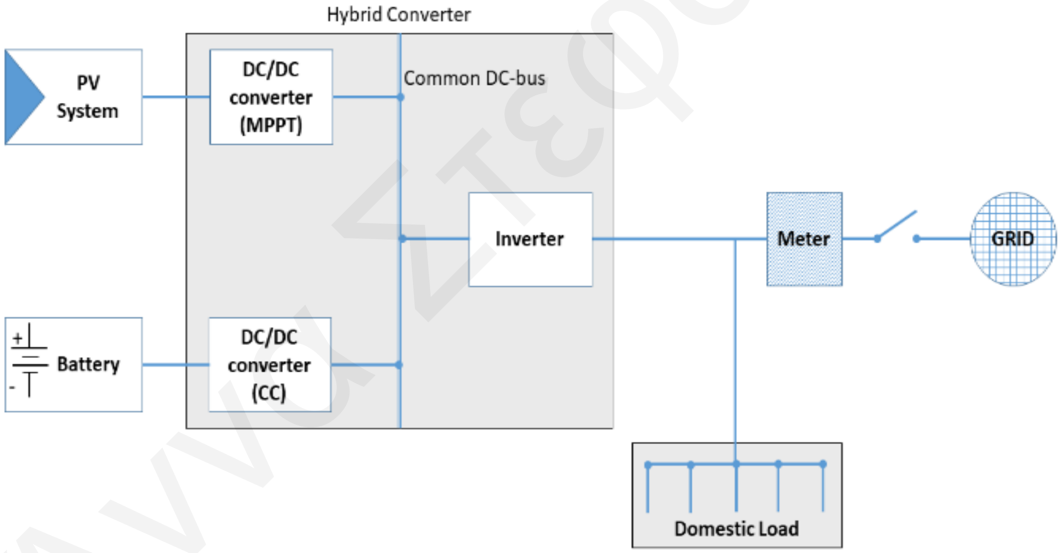


Figure 4. *Schematic diagram for the DC-Coupled "Hybrid" system.*

2.2.1. System Design Parameters

A proper design of PV-BES system requires careful selection of the power converter and the battery unit of a BES. This section describes the minimum electrical and environmental requirements of the BES for a residential PV-BES system (either DC-Coupled or AC-Coupled) [32], [33].

Table 1. *Comparison of AC-Coupled and DC-Coupled system topologies.*

	AC-Coupled	**DC-Coupled**
Pros	• Flexible installation to existing systems • Easily expandable	• Fewer components • Higher efficiency
Cons	• Less efficient requiring both PV and Battery converters	• Existing PV converter cannot be reused. • Expensive to upgrade

Electrical Parameters

Converter Nominal Power: The power rating of the converter is a critical parameter when designing a coupled PV-BES system regardless the topology. The converter maximum grid power must adhere to the national grid codes of each country whereas the nominal PV input power must be at least equal to the peak power of the PV array based on seasonal variations, i.e. ambient temperature and solar irradiation variation through the year. If this condition is not fulfilled, part of the PV produced energy will be lost as the power converter will be underperforming. In terms of the converter battery input, the battery nominal power defines the charging and discharging time of the battery unit. It also determines the maximum load the converter is capable to withstand or feed back to the grid. Consequently, this affects the ancillary grid services the PV-BES can provide such as voltage and frequency regulation and islanding. Finally, the rated power is usually given under specific ambient temperature (i.e., 25°C), hence the power derating curves provided by the manufacturer must be considered when selecting the maximum operating converter power at higher temperatures such as the case of Cyprus. Taking into consideration the above guidelines, the converter power efficiency should always remain above 95%.

Nominal Voltage: The converter nominal voltage should be rated at the nominal grid voltage and be able to operate within the voltage margin allowed by the national grid codes; for instance, the grid voltage range in Cyprus is 230±10%. Also, it is recommended that power converters conform with EN61000-3 standard which is related to short voltage changes, fluctuations, and flicker. Also, when the PV-BES system will be designed for islanding conditions, the converter shall keep the voltage regulation within the acceptable range defined by the grid codes when the grid is unavailable. In terms of DC input range, the converter nominal voltage should be capable to handle the peak PV system voltage to ensure that the converter is able to withstand the maximum PV array as the ambient temperature decreases [34]. Finally, the converter input voltage on the battery side is also a significant parameter because it changes with the remaining battery capacity. The converter voltage range should be greater than the minimum and maximum voltage of the battery.

Nominal Frequency: The converter should be able to operate at the nominal frequency of the grid (50Hz). Additionally, the converter must remain active during over or under frequency circumstances (less than 47 Hz or more than 51.5 Hz) to assist in frequency regulation, if desired.

Total Harmonic Distortion (THD): In order to ensure proper power quality at the converter output, the converter should comply with the relevant standard EN61000-3-2. Otherwise, it is possible that the inverter will interfere with other devices on the network and their performance will degrade. It is recommended that the THD ratio of the converters to be lower than 5%.

Power Factor (PF): The converter PF should be adjustable within the acceptable range defined by the grid codes i.e., between 0,9 leading and 0,9 lagging and be able to aid in regulating the voltage of the grid through compensating reactive power, either absorb or supply to the distribution grid.

To summarize, the electrical characteristics of the coupled PV-BES system should be selected carefully to guarantee that the efficiency of the system will remain high. Apart from this, the converter and battery units in a PV system should also conform with standards related to electrical safety and operation. Table 2 presents the minimum recommended standards which were extracted from the LV Directive and the Electromagnetic Compatibility Directive.

***Table 2**. Minimum recommended standards for power converters*

Category	Standard	Description	Converters	Battery Unit
EMC	EN61000-3-2[1]	Harmonic current emissions	✓	
	EN61000-3-3[1]	Voltage changes, fluctuations and flicker	✓	
	EN61000-6-1	Immunity.	✓	✓
	EN61000-6-3	Emissions.	✓	✓
Electrical Safety	EN50178	Power electronic converters and equipment.	✓	✓
	EN62109	Power converters for PV systems (applicable only for PV and Hybrid converters)	✓	
Battery Safety	IEC62281	Transportation testing for lithium batteries.		✓
	IEC62133	Safety test for lithium batteries.		✓
	EN62619	Safety requirements for secondary lithium cells and batteries.		✓

Mechanical Parameters

Ingress Protection (IP): Electronic equipment derating due to exposure to unwanted environmental conditions is a significant parameter to take into consideration when high system performance is needed. IP is a rating that grades the resistance of the electronic equipment against the intrusion of dust and liquid. In the case of the coupled PV-BES residential system, a minimum IP40 rating is recommended for all devices of the system to ensure protection from tools and wires greater than 1 millimeter. For outdoor electronic devices, a minimum of IP65 is recommended such that the equipment is totally protected against dust and low-pressure water jets.

---

[1] Standards EN61000-3-2 and EN61000-3-3 apply to electrical and electronic equipment that have an input current of up to 16A per phase, suitable for connection to the low-voltage AC grid.

Ambient Temperature and Relative Humidity: The recommended operating range of the electrical and electronic devices of the equipment should safely operate within the range of –40oC and 50oC and 5% to 95% for ambient temperature and relative humidity respectively. However, the lithium battery unit is sensitive to very high or low temperatures and its lifetime degrades faster when exposed to unwanted temperatures. Therefore, an operating temperature range of at 25oC ± 10oC is considered acceptable for lithium-based batteries.

Cooling: To ensure proper heat dissipation and keep the equipment performance to the maximum, it is proper to choose natural convection for units that will be installed indoors to eliminate any induced fan noise, and forced air cooling for units that will be installed outdoors.

In addition to the electrical and mechanical parameters, the establishment of uninterrupted communication and data exchange across the several units of the PV-BES system is another important requirement. For instance, the information collected by the bidirectional energy meter or Smart Meter (SM) like the grid imported and exported energy along with other measurements such as voltage, frequency, harmonics and power factor, is important to be exchanged with the central EMS in regulating the energy flow and optimizing the system behavior depending on the desired storage dispatch strategy. It is important to have a unified communication protocol across all the components of the PV-BES system. Usually, SMs support serial communication such as RS-485 or Modbus, a serial protocol allowing fast and reliable data transfer along long distances. More recently, SMs also support data communication over TCP/IP interface that runs over Ethernet cable.

3. Methodology

The methodology that was followed in this thesis is depicted in Figure 5. It contributed to the development of a procedure that can be used to optimally size a BES system for residential use in conjunction with an existing PV system, targeting to maximize self-consumption. The details of each individual part of the procedure are discussed in the following sections.

Data were collected from a group of residential users with existing PV system (prosumers) over a period of 1-year and the data filtering process (identification and construction of

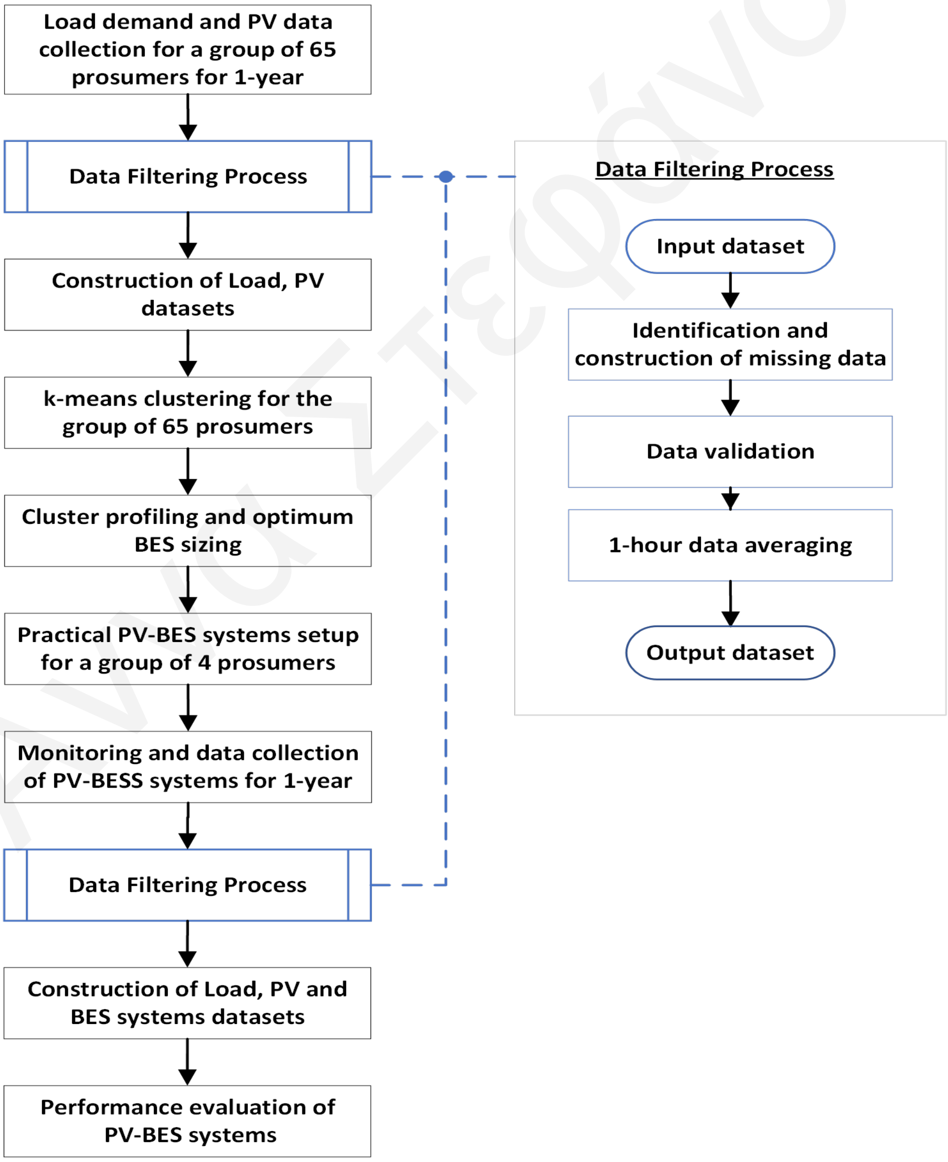


Figure 5. *Flowchart of the proposed methodology used in this thesis*

missing data, data validation) was first applied to construct the PV and load demand datasets. A load characterization procedure was then applied using the collected datasets to reveal the daily energy needs, and finally to cluster the prosumers based on the daily import electricity needs. Next, a BES system sizing process followed to determine the required BES capacity and power that can maximize the PV self-consumed energy. By considering the BES sizing calculations, four PV-BES systems were installed in residential premises as pilots for this work through the StoRES project which is co-financed by the European Regional Development Fund (ERDF) through the Interreg MED Programme under the grant agreement number 1MED15_2.2_M2_184. Following the pilots monitoring over a period of 1-year, the data filtering process was again applied on the acquired data to construct the energy datasets of the pilots. Finally, the performance of the PV-BES systems was evaluated, and the self-consumed energy was compared to the theoretical values without the BES system installed.

3.1.Data Collection and construction of PV and load datasets

A group of sixty-five (65) prosumers in Cyprus was selected, in the prospect of designing a procedure to optimally size a BES system coupled with a 3kWp PV system under the Net-Metering scheme. All participating prosumers were geographically spread throughout the island to cover different societal and geographical situations. Two SM devices were installed as depicted in Figure 6 to measure the energy profiles for each prosumer. In particular, one SM device was placed on the AC-side of the PV power converter to measure the PV generation and the second was placed on the grid side to measure the energy exchange with the grid (i.e., import and export electricity). The SM were single-phase bidirectional meters that logged 30-minute average values. The datasets were post-processed, and the desired parameters were post-calculated and stored to a central database platform.

Particular emphasis was given on the energy demand of the households, since by achieving demand response from the user, could efficiently minimize issues related to the gradual increase of PV deployment to the grid. At the same time, electricity consumption depends on the daily habits and societal level [35] of the individuals. Towards this direction, the process of collecting energy datasets from the 65 participating prosumers began in 2015

Grid exchange electricity data, like import and export electricity as well as PV production data, were collected and used for the clustering process described next.

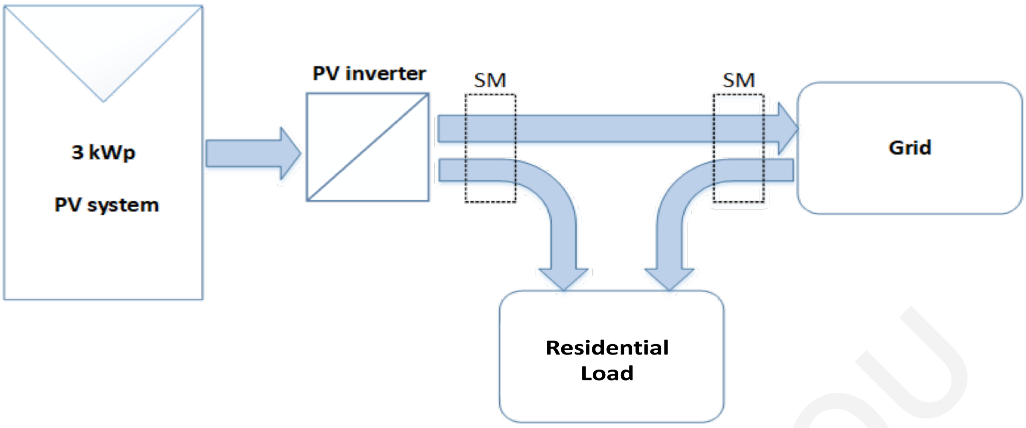


Figure 6. *Schematic diagram of a residential PV system using Smart Meters.*

3.2. Prosumers Clustering and BES sizing

The clustering process uses the datasets acquired from the group of the 65 prosumers to categorize them based on the import energy samples, as they provide a significant indication of the additional energy required to achieve grid balance. As a consequence, the cumulative daily import electricity values (in kWh) were extracted for all participating prosumers throughout the test year and were used for the grouping process. Then, the *k*-means technique was adopted to perform the characterization between different import energy profiles and gain knowledge about the grid interaction of the prosumers. The *k*-means method uses fixed input dimensions, in this case the import energy time series of each user, to separate them based on the input data-series [36]. The algorithm uses an autocorrelation-based process to compute a dissimilarity vector between the time series as a function of the weighted Euclidian distance expressed in Eq. 1 below [37], [38].

$$d_{ACF} = \sqrt{\left(\hat{\rho}_{X_T} - \hat{\rho}_{Y_T}\right)^T \Omega \left(\hat{\rho}_{X_T} - \hat{\rho}_{Y_T}\right)} \qquad (1)$$

The parameters $\hat{\rho}_{X_T}$ and $\hat{\rho}_{Y_T}$ are defined as the autocorrelation vectors of X_T and Y_T time-series respectively with length L, whereas Ω denotes the weight coefficient matrix. For this study, the weight matrix was chosen to be identical such that $\Omega = I$, letting Eq. 1 become:

$$d_{ACF} = \sqrt{\sum_{i=1}^{L}\left(\hat{\rho}_{X_T} - \hat{\rho}_{Y_T}\right)^2} \tag{2}$$

Once the Euclidian distance was calculated, the k-means clustering technique was applied. The idea behind clustering was to partition the observations with length L into k sets $S = \{S_1, S_2, \dots, S_k\}$ such that $L \leq k$. Finally, the k-means clusters were derived as in Eq. 3, where μ_i is the mean of points in S_i.
Recalling the fact that the number of clusters k must be known priori and are user-defined, the elbow method was used to identify the optimum number of clusters that the data was partitioned to. This is expressed in Eq. 4, where the variable k was chosen such that the total intra-cluster variation, also known as the within-cluster sum of squares (WSS) was minimized. The parameters $W(C_k)$ denotes the intra- cluster variant of sequence C_k, where k is the number of clusters in each iteration, ranging from 1 to K clusters.

$$argmin \sum_{i=1}^{k} \sum_{x \in S_i} \| x - \mu_i \| \tag{3}$$

$$wss = \min\left(\sum_{k=1}^{K} W(C_k)\right) \tag{4}$$

This resulted to the user's classification based on the grid-imported electricity behavior and also it categorized the prosumers into groups. However, considering the environmental variations throughout the year, which affect the PV generation and, hence the power demand of end-users, the BES dimensioning with respect to capacity levels, was performed seasonally. The test year was divided into three main periods, the summer, winter and intermediate as shown in Table 3. Next, the annual import profile of each cluster was divided seasonally, and the average seasonal BES capacity of each period was determined. As a result, the accumulated daily electricity import of each period was determined, which reflected the additional electricity that the BES needed to compensate during each season.

Additionally, a comparison between the desired BES capacity and the cumulative daily PV export of the prosumers within the same cluster was performed. This provided an indication of the number of end-users with enough surplus energy to satisfy the average BES size allocated to each cluster. For this work, the deep-cycle Lithium-based BES technology was considered for the battery capacity calculation of each cluster. Assuming that the AC-Coupling topology was chosen, an approximated system round-trip efficiency of 90% was considered. The 10% loss was assumed to be on the AC-to-DC and DC-to-AC conversion, in the BES system itself and the cable losses. Finally, a power analysis of the users was examined. The 30-minute import power measurements were used to study the instantaneous import power profile of each cluster seasonally and gain insights about the power dimensioning of the BES converter.

Table 3. *Seasonal clustering of Reference Year*

Season	Days of year	Period Length
Summer	May – August	123
Winter	Jan – Feb, Nov-Dec	121
Intermediate	March – April, Sep-Oct	121

3.3. Practical Pilots Setup

3.3.1. Systems procurement and installation

The clustering analysis provided a useful methodology for sizing a coupled PV-BES system tailored for residential use in Cyprus. The BES converter power and battery capacity parameters were determined by the clustering process and the minimum electrical and environmental system specifications were incorporated into the tender specifications for the procurement of the BES systems in Cyprus. An open tender was organized by the University of Cyprus (UCY) to procure four (4) BES systems for residential premises. The tender was coordinated and administrated by the Procurement office of the UCY. Following the drafting of the tender specifications, a consultation process was initiated inviting companies and interested parties to comment on the tender documents. Next, the official tender was published through a governmental public procurement platform where vendors were encouraged to participate in the bidding process. Upon technical and financial evaluation of the offers, a 2.5kW/9.8kWH AC-Coupled system has been evaluated as the top-scoring BES system and procured in Cyprus.

Moving on to the pilot installation phase, was considered as the first notable step towards integrating BES in the LV distribution grid and validate storage technology potential for increased PV penetration. Four residential pilot sites were selected through a transparent process. The pilot sites consisted of residential prosumers with an existing PV system and complied with the local regulations regarding the permitted PV capacity. According to the

Distribution System Operator (DSO) of Cyprus, eligible installations under Net-Metering scheme were residential PV systems with maximum installed capacity of 4 kWp for single-phase systems and up to 5kWp for three phase systems (as of 2018 regulation). Consequently, the pilot selection process was organized between the UCY and the DSO to coherently determine the suitable premises. For provisioning purposes, the selection of the pilots was focused on a single LV feeder with high penetration from RES such that optimal storage utilization and smart energy management features could also be examined in a future investigation. The selection of the LV distribution feeder was performed using the capabilities of the DSO's Geographic Information System - GIS which records the distribution network data. The LV feeder was located in a residential area in Nicosia and used a 500kVA 11kV/415V power transformer that connected twenty (20) residential households, with seven (7) existing PV systems operating under the Net-Metering scheme.

The households that participated in the pilot phase were determined through an audit process which was initiated in close collaboration with the DSO to eliminate any practical issue during the system installation and also ensure that the installation environment complied with the equipment specifications. The premises that were selected by the evaluation process are shown in Figure 7. Photos from the pilot systems installations are provided in the Appendix, where the existing PV systems capacity of the selected pilots are 3kWp and 3.5kWp. Upon equipment installation and system inspection by the DSO, the residential pilot systems were set for a trial operation with duration of one year starting from January until December of year 2019 (hereby referred as the reference year). Performance and energy data including PV energy yield, BES charge and discharge power, grid import and export power and battery SoC were taken in 15-minute average values and stored in a secure cloud-based platform for post processing and analysis.

3.3.2. Coupled PV-BES system overview

The installed PV-BES solution coupled the PV and BES on the AC-side and the BES. A bidirectional power converter with rated power of 2.5kW was used compatible with the Lithium-Iron Phosphate (LiFePO4) batteries that were selected for the pilot systems. The battery units were high voltage (400VDC) with a nominal capacity of 9.8kWh and a Depth of Discharge (DoD) up to 95%, offering a usable battery capacity of 9.3kWh at a round-trip efficiency of 90%.

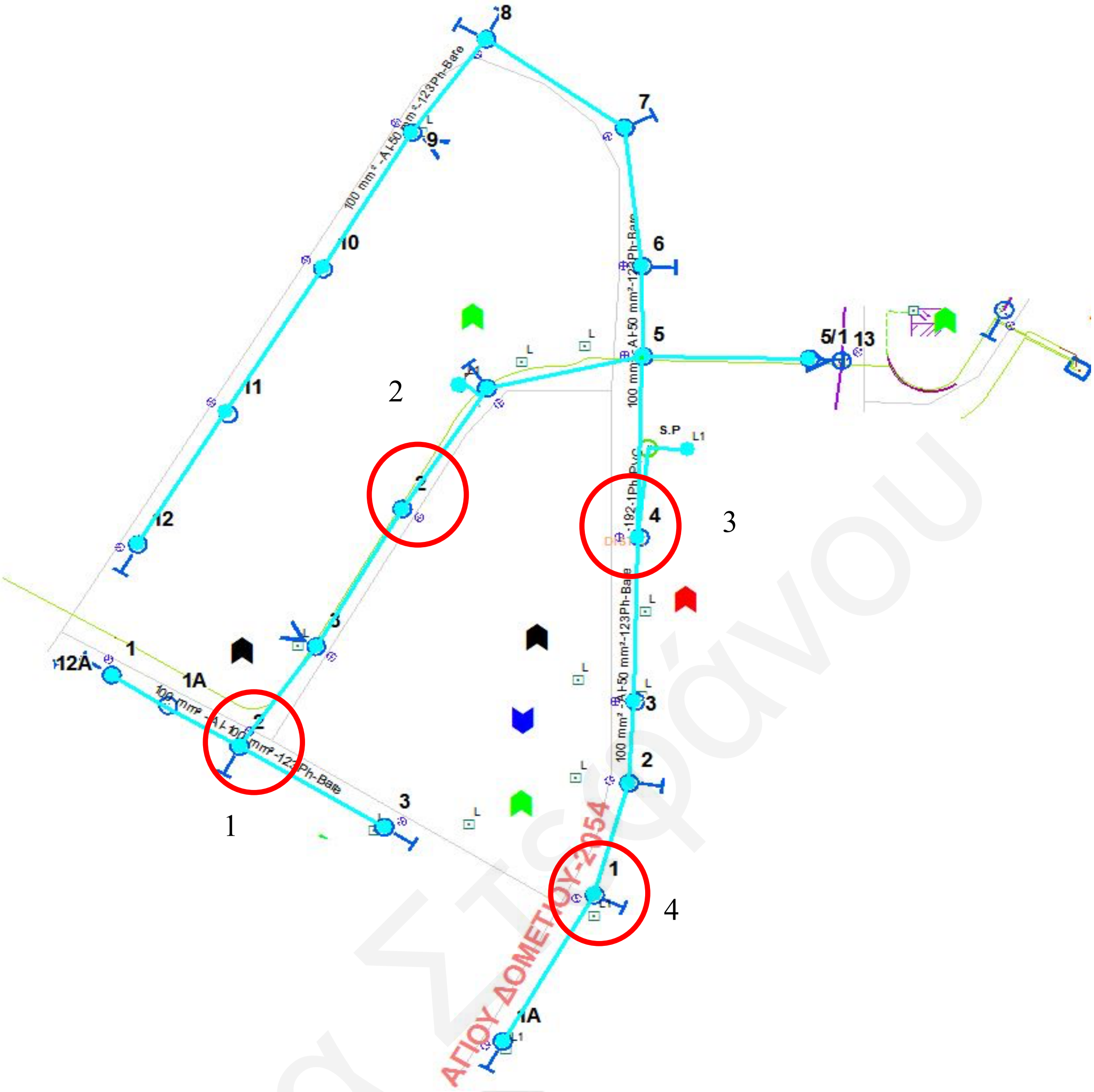


Figure 7. *Schematic diagram of the LV Distribution feeder.*

Auxiliary equipment was used; two (2) bidirectional power meters accompanied the BES system, which were used as external metering devices. A grid power meter was placed behind the traditional utility meter and measured the energy exchange with the power grid in 15-minute average values. In addition, the device was equipped with communication interface which allowed for for data collection by the system EMS, responsible for making decisions concerning the behavior of the system. Also, a PV power meter was placed after the PV power converter for measuring the PV output, and 15-minute data were sent to the EMS via a local communication link. Consequently, the integration of the metering devices provided the capability for collecting power and energy measurements from the interconnected household, whilst the EMS was performing energy management strategies to achieve the target of the desired dispatch mode. The EMS of the selected system supported many dispatch modes such as active power limiting, battery scheduled charging and Time of Use tariffs. For the purposes of this work, the Target Zero (TZ) algorithm, which will be described next, was selected as the main dispatch strategy in order to maximize the self-consumed PV energy on the premises. Other important system specifications included the IP55 protection rating and the 0-45°C operating temperature range, allowing the system to be installed outdoors and operate under the high temperature conditions of Cyprus. An overview of the system technical specifications is shown in Table 4, where a detailed documentation of the PV-BES solution is provided in Appendix.

Table 4. *Overview of the AC-Coupled BES system specifications.*

	Power Converter	**Battery Unit**
Rated power (230V, 50Hz)	2.5kW	-
Total/Usable Capacity	-	9.8/9.3 kWh
PF displacement	0.8 leading - 0.8 lagging	-
Max Efficiency	96.1%	>95%
DC Voltage Range	100-500V	400-450V (charging) 350-430V (discharging)
Operating Temperature Range	-40 °C to 60°C	-10 °C to 45 °C
Max AC Current	11A	-
Rated/Max DC Current	10A/18A	10A (Charging) 14.3A (discharging)
Degree of Protection	IP65	IP55

3.3.1. Online Monitoring Platform

The pilot systems were monitored through the online platform provided by the system vendor. It consisted of a complete monitoring system and was tailored to log system parameters such as PV energy yield, load profile and BES behavior in 15-minutes resolution. Regarding the user management, different roles were created to provide access to UCY and DSO personnel as well as the premise owners. A standard user role was assigned to the end-users with access being restricted only to instant system information, historical energy yields and system properties, whereas a full user role was assigned to UCY and DSO providing the flexibility for editing the system configuration and properties.

Data visualization was provided for live and historical system data preview using a two-stage plot as shown in Figure 8**.** The upper half of the plot shows the overall load consumption and identifies the source of energy the household has been supplied from such as the PV system, BES system or grid. The lower half of the plot depicts the total PV power profile and shows when and how much yield has been used for direct consumption, BES charging or injected to the grid.

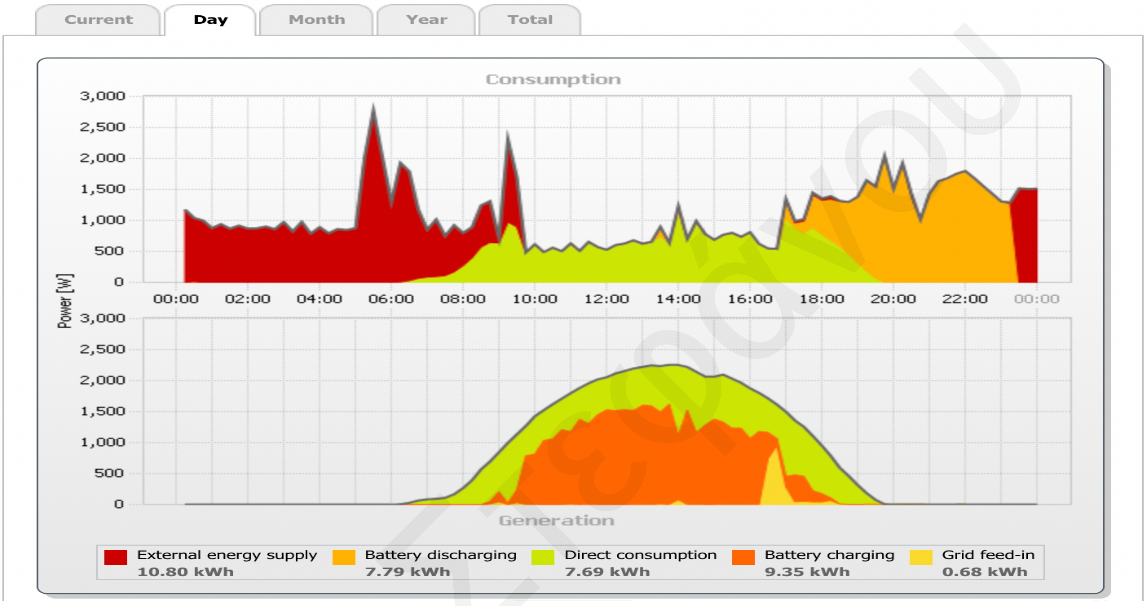


Figure 8. *Daily energy balance of a pilot system.*

3.4. Performance evaluation metrics

In this section, the most important indications are presented as they were used to evaluate the performance of the pilot systems. Starting with the energy dispatch methodology, many strategies exist for operating the BES such as peak power saving that proactively limits the overall demand to a desired level. More advanced dispatch algorithms take into consideration weather metrics (i.e., ambient temperature, wind speed etc.) to perform day ahead PV generation and load demand forecasting with the aim to schedule the BES behavior for reducing the electricity cost [39]. Due to technical limitations set by the DSO, the BES would be restricted to charge only from the surplus PV electricity. Also, since the electricity tariffs for import and export electricity were equal (premises under the Net-Metering scheme), there was no financial benefit if load shifting mechanisms were applied. Therefore, TZ algorithm was adopted since it is the only dispatch algorithm suitable for reaching maximum self-consumption rate (SCR) for premises utilizing only the surplus PV electricity. The TZ algorithm prioritizes generated PV energy for supplying the local load demand and the BES charging, before feeding the surplus energy to the grid. The BES charging was strictly limited to the excess PV electricity, meaning that the power converter could not charge the BES from the grid. The objective function for the TZ algorithm was defined using Eq. 5 [40]. The parameters P_{rated} and E_{rated} denote the rated power (in kW) and the rated battery capacity (kWh) respectively, and they were selected to correspond to the specifications of the selected BES system. The target battery power for the residential load P_{target} was the instantaneous power required from the BES system and was calculated as the difference between the instantaneous premise load P_{load} and the PV generated energy P_{gen}. The target power was then compared with the system rated power and was adjusted to it if necessary. Also, the available energy level of the battery was calculated. If the stored energy exceeded the rated levels, then the BES power was set to zero, otherwise it was set to the target power level. Positive values of P_{bat} denote that the battery was discharging while negative values denote that the battery was charging.

$$P_{target}(t) = P_{load}(t) - P_{gen}(t), \qquad where$$

$$P_{bat}(t) = \begin{cases} \min\left(P_{target}(t),\, P_{rated}\right), & if\ P_{target}(t) > 0\ \ and\ \ E_{bat}(t) \geq 0 \\ \max\left(P_{target}(t), -P_{rated}\right), & if\ P_{target}(t) < 0\ \ and\ \ E_{bat}(t) \leq E_{rated} \\ 0, & otherwise \end{cases} \tag{5}$$

The parameter $E_{bat}(t)$ quantified the available BES energy level that was stored in the battery unit at a given time *'t'*. The ratio of the available battery energy $E_{bat}(t)$ over the rated battery capacity $E_{bat\,rated}$ was defined as the battery State of Charge (SoC) and was expressed as a percentage (Eq. 6).

$$SoC(t) = \frac{E_{bat}(t)}{E_{bat\,rated}}\, x\ 100\% \tag{6}$$

Maximizing the self-consumed electricity was the main objective of the TZ algorithm. The SCR for pure PV and load system was expressed with Eq. 7 and was quantified as the ratio between the PV produced energy and the portion of the PV production directly consumed by the load. Since we were dealing with a coupled PV-BES system, the SCR was re-expressed with Eq. 8 to consider the amount of energy that was stored in the BES system.

$$SCR_{PV} = \frac{Direct\ PV\ Consumed}{Total\ PV\ Production}\ x\ 100\% \qquad (7)$$

$$SCR_{BES} = \frac{Direct\ PV\ Consumed + BESS\ charge}{Total\ PV\ Production}\ x\ 100 \qquad (8)$$

The above performance metrics were used to examine the performance of the pilot systems. More specifically, the SCR of the pilots was extracted from the pilot systems over the reference year and was compared to the accumulated SCR performance without the BES system. Finally, the SoC datasets of the systems were assessed as they provide an important parameter related to the capacity of the BES system.

4. Results

4.1. Prosumer Clustering Analysis

The WSS method was used to determine the number of clusters for the k-means clustering technique. The WSS plot is shown in Figure 9 and represents a graphical demonstration of the intra-cluster variation for a range of cluster values. The optimal *k* value was retained from the elbow point, and in this case the prosumers datasets were grouped in three (3) clusters based on the daily grid import electricity. The most dominant user group was Cluster 3 with 34 out of 65 users (52%), where Cluster 1 followed with 20 users (31%) and finally Cluster 2 with 11 users (17.0%). The clusters revealed similar behavior over the tested year, however with different energy levels as this varies according to the seasonal and geographical conditions as well as the societal level. The grid import energy reaches significantly higher levels during the summer period as the ambient temperature peaks and electricity demand for ventilation and cooling increases. On a similar line, import electricity is high during winter months due to increased demand for heating. The intermediate period is a transitional stage between summer and winter months as the grid import electricity levels remained relatively low. Taking into account that the PV yield is maximum during this season, a significant share of power demand is supplied directly from the the PV production. The import electricity profile for each cluster is depicted in Figure 10.

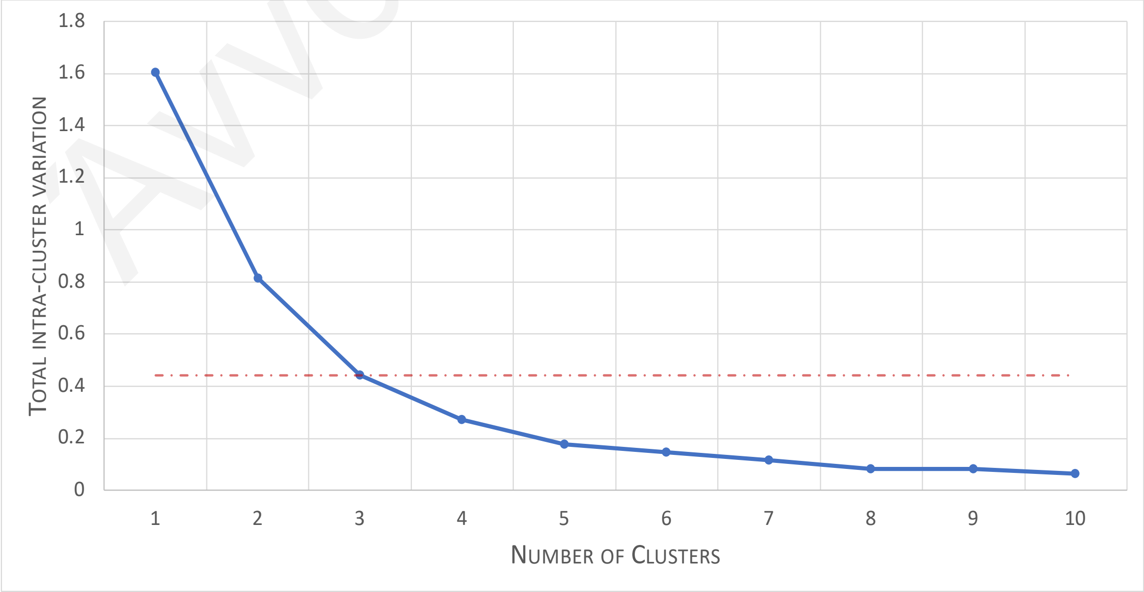


Figure 9. *Intra-cluster variation of import energy datasets.*

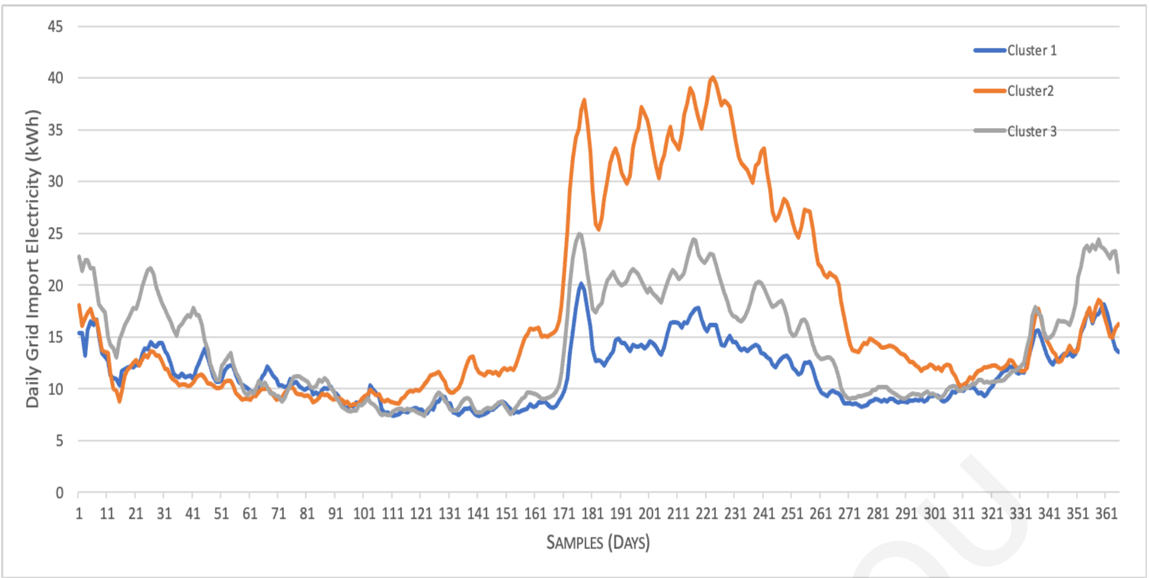


Figure 10. *Average daily import energy of the user Clusters over the test year.*

4.2. AC-Coupled BES system sizing

Following the clustering analysis, the import power and energy datasets were analyzed for each cluster as they provided important information regarding the dimensioning of the BES system. Beginning with the dimensioning of the system power rating, the converter should be capable of suppling the maximum load power demand in a way to minimize the power flow coming from the grid side. To determine this, the 30-minute import power data were analyzed for each cluster and the results are depicted using box-whisker plots in Figure 11. Focusing on Cluster 1 and Cluster 3, they both followed a similar distribution with mean power of 0.53kW and 0.66kW respectively and a significant number of outliers during the winter period, which reveals that the power demand was extremely volatile. Also, the average power of the clusters did not change severely during the entire test period. Moving on to Cluster 2, the wide interquartile region (IRQ) during the summer period which ranges between 0.43kW and 1.61kW as well as the enormous power levels of the outliers, verifies the higher load demand of this user group. The box-whisker plot is utilized for the BES power sizing by selecting the maximum seasonal observation (excluding outliers) as the rated power of the converter. The maximum import power observations ($\hat{P}_{\text{imp}}$) for the clusters derived by the process are shown in Table *5*. Thus, the rated power of the battery converter was chosen at 2.2kW, which represents the average annual average of Cluster 2. This is to ensure that the converter can supply the maximum expected power rate and maintain efficient power conversion by operating the converter close to the maximum efficiency point of the converter. In terms of capital expenses, the cost of the power converter is relatively low compared to the battery, therefore the cost difference by oversizing the power converter is not significant.

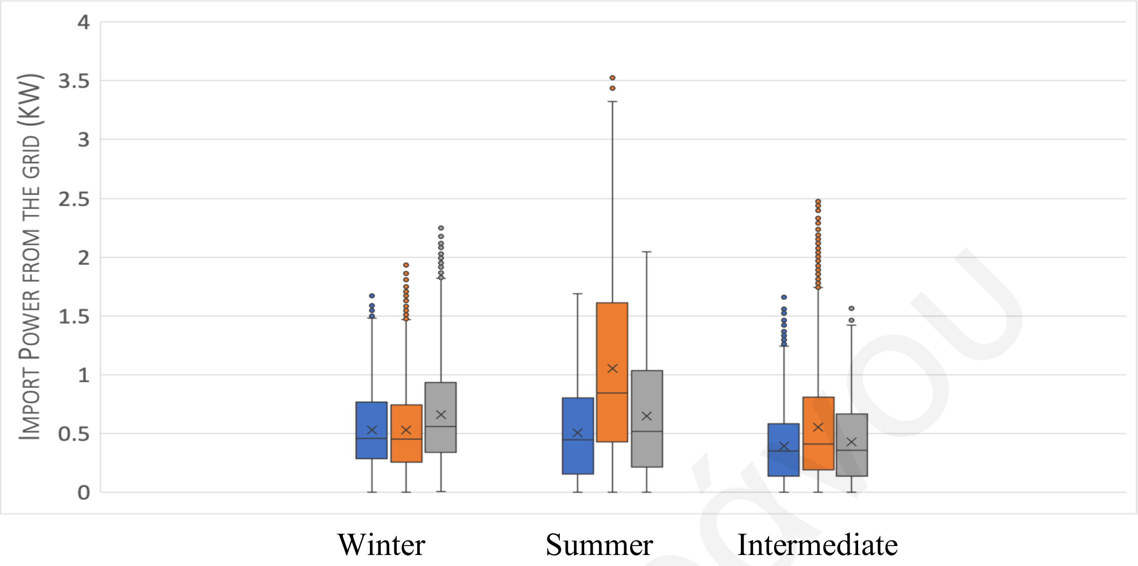


Figure 11. Seasonal import power range of each cluster.

Moving on to the battery capacity sizing, a more extensive analysis was required as the battery cost is high and comprises the most expensive component of the entire AC-Coupled solution. The battery capacity selection begun with the analysis of the daily import observations for each cluster as shown in Table 5, where Cluster 1 scored the lowest mean grid imported energy ($\bar{E}_{\text{imp}}$) during the entire test year, that is 11.9kWh. Cluster 3 which is the most dominant user group, yields to an average import energy of 14.5kWh, where Cluster 2 reported the highest level of 25kWh per day. The high import energy levels extracted during the test year verify the small direct contribution of the existing PV systems to the load demand. Considering that the estimated annual PV yield in Cyprus, is around 1600kWh/kWp per year (or 4.4kWh/kWp per day) PV system oversize may be needed to achieve grid balance [41], [42].

The analysis gained insights about the behavior and interaction of residential users with the grid over the entire test year. However, for choosing a suitable battery capacity the surplus electricity that is fed back to the grid should also be taken into consideration as the

Table 5. *Cluster average import energy and peak power*

	Cluster 1		Cluster 2		Cluster 3	
	$\hat{P}_{\text{imp}}$ (kW)	$\bar{E}_{\text{imp}}$ (kWh)	$\hat{P}_{\text{imp}}$ (kW)	$\bar{E}_{\text{imp}}$ (kWh)	$\hat{P}_{\text{imp}}$ (kW)	$\bar{E}_{\text{imp}}$ (kWh)
Winter	1.4	12.7	1.5	12.8	1.8	15.9
Summer	1.7	12.1	3.3	25.0	2.1	15.6
Intermediate	1.3	10.7	1.8	13.6	1.4	12.1
Average	1.5	11.9	2.2	17.1	1.8	14.5

BES system ideally stores excess PV generation for later use. Towards this direction, the export energy datasets were studied to validate the sufficiency of the seasonal surplus energy delivered to the grid. A similar box-whisker plot analysis was performed on the daily export electricity datasets and the results are illustrated in Figure 12. The analysis revealed higher export electricity levels during the intermediate period, whilst the lowest surplus electricity occurs during the winter period. Furthermore, the users' adequacy to supply the average cluster energy requirements (see Table *5*) was then compared with the surplus energy levels of users within the same cluster, reduced by a factor of 10% to emulate BES round-trip efficiency losses. The desired BES capacity was chosen such that 20% to 80% of the participating users would have adequate surplus energy levels. The analysis results are illustrated in Figure 13. For instance, a suitable battery capacity for users that lie in Cluster 1 can range between 55-70% of the average cluster import energy i.e., 6.5 – 8.2kWh. The BES capacity for Cluster 2 was limited due to the high import energy needs and could be scaled up to 40% of the average cluster import level or 6.8kWh. Finally, Cluster 3 achieved the highest surplus energy levels, allowing the sizing of the battery capacity to range up to 8.0kWh. By comparing the analysis results, it was noted that the upper bound of the capacity range revealed for Cluster 1 and Clusters 3 is almost identical, therefore an 8.2kWh is the selected BES usable capacity that can potentially maximize the SCR of the tested premises[36].

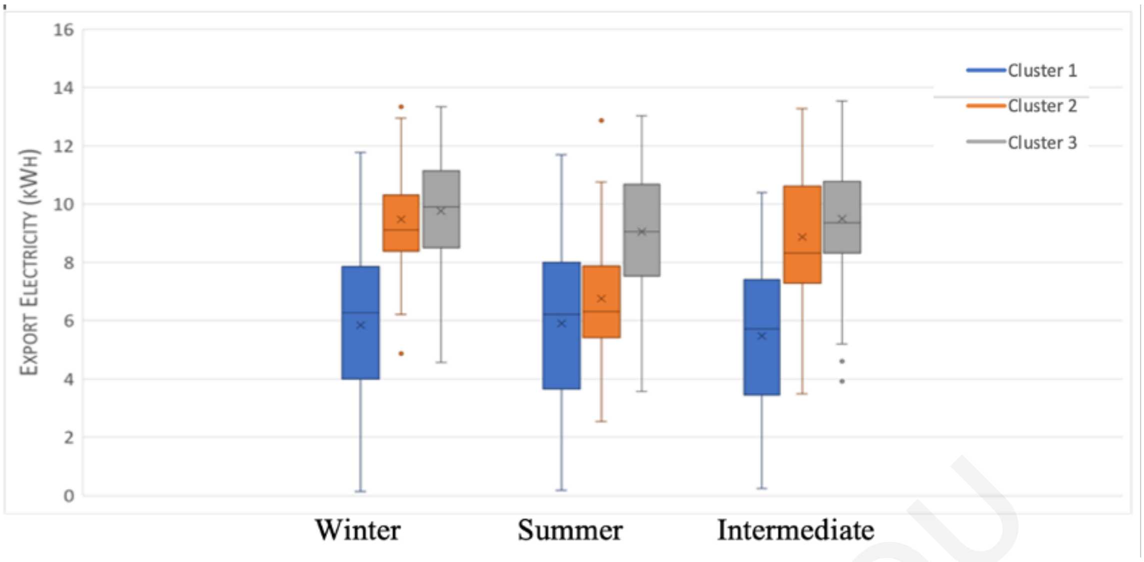


Figure 12. *Seasonal export power range of each cluster*

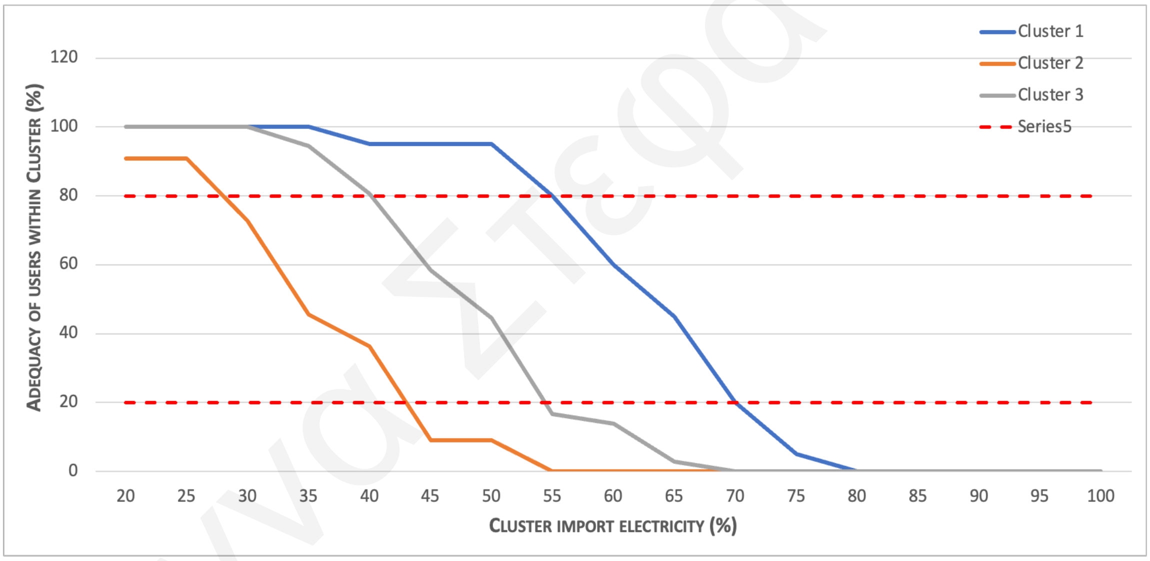


Figure 13. *Export energy adequacy to meet cluster import energy requirements.*

4.3. Pilot Systems Evaluation

With the TZ management method being applied to the EMS of the coupled PV-BES system, the data were collected during the reference year and post-processed to evaluate the impact of energy storage to residential premised with existing PV system. More specifically, the pilot sites behavior was examined in terms of the exported and imported energy to the utility grid as well as the SCR before and after integrating the BES system to the existing PV systems.

To begin with, there is an enormous reduction on the average daily energy that was spilled to the utility grid, ranging between 4.1kWh and 7.4kWh compared to the export energy values of the scenario without BES system. This is illustrated in Figure 14 where the PV-BES solution brings in a significant cut on the average electricity export as this is locally stored to the BES system for later use. Considering this, and also the fact that the daily energy yield of the four pilot sites was 13-17kWh (i.e., 3kWp or 4kWp PV system), it can be said that a significant share of 30-48% of the daily yield was injected to the utility if the local storage system was not utilized, verifying that residential load pattern does not coincide with the PV yield profile. The integration of BES to the existing PV systems confined the energy spilled up to 95% for Pilots 2, 3 and Pilot 4, where for Pilot 1 the reduction rate remained low at 55%.

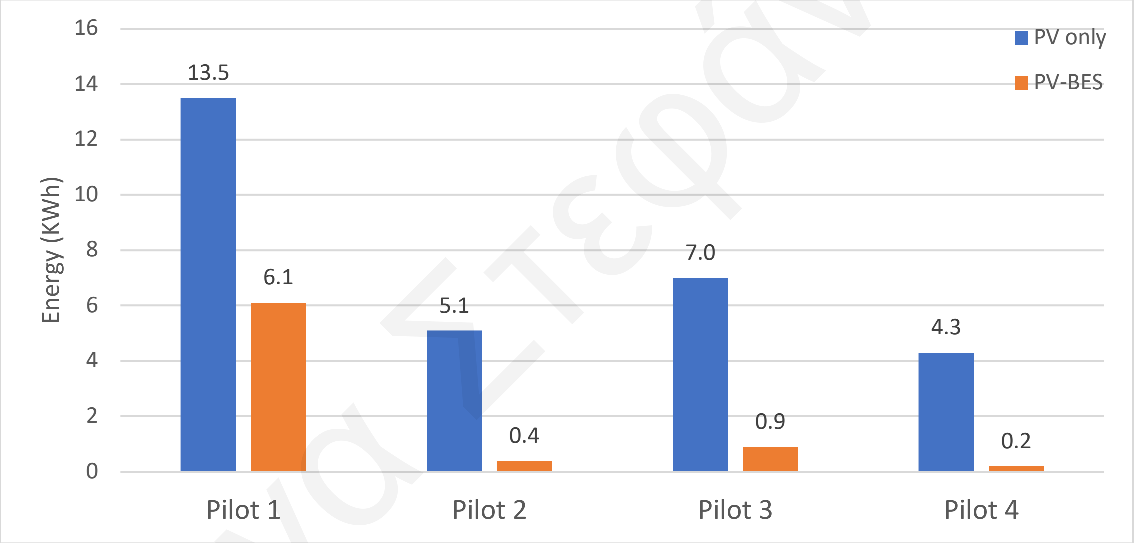


Figure 14. *Comparison of daily export energy before and after BES integration.*

Similarly, the coupling of BES system to existing PV systems brought a considerable reduction on the daily imported electricity as well. According to the TZ energy management logic, the available energy was dispatched to supply the residential load demand during low PV yield conditions. The import energy levels recorded during the reference year are illustrated in Figure 15 along with the import values, assuming the absence of the BES system. The reduction of the import energy ranges between 3.4-5.9kWh per day which was clearly lower than the export energy cut shown previously. This was related to the operating efficiency of each system and on the system round-trip efficiency and the environmental conditions each system was exposed to. For instance, Pilot 4 contributed the highest export energy rate of 95% or 4.1kWh per day, however the actual impact on the import energy was 3.4kWh per day. This resulted to an overall system efficiency of 83%, causing 0.7kWh to be lost during the energy cycling through the BES system. Taking into consideration the system round-trip efficiency of 10% (i.e., power conversion losses, cable losses), additional performance loss was induced to the system which stemmed from the performance derating due to environmental conditions violation. For instance, additional efficiency loss was induced when the BES operating temperature exceeded the maximum level of 30°C which is very likely to occur during the summer period in Cyprus.

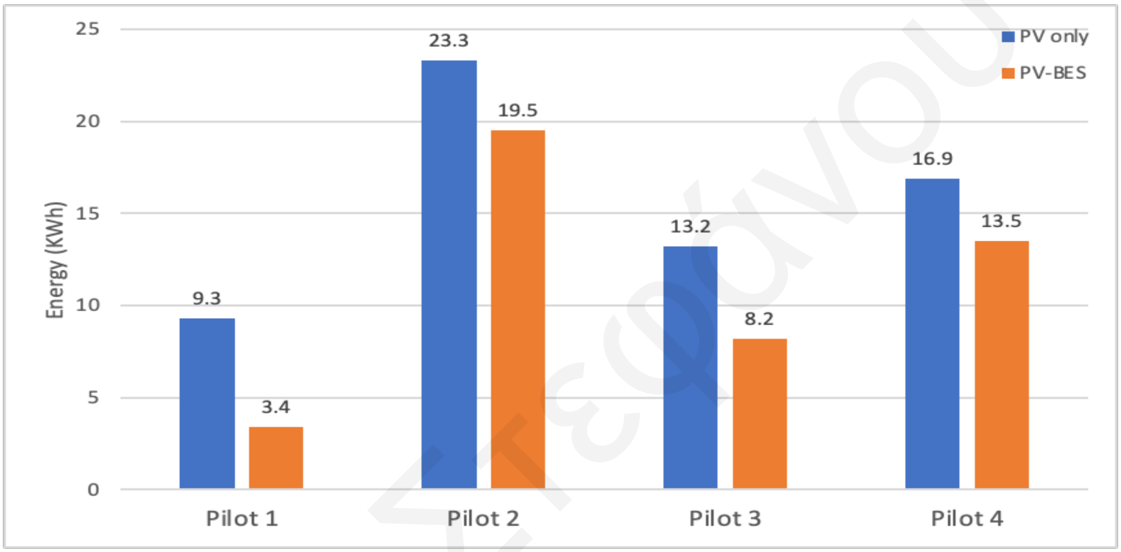


Figure 15. *Comparison of daily import energy before and after BES integration.*

Further to this, by examining the behavior of Pilot 1, it can be seen that it contributes the lowest reduction rates of 55% and 63% on the daily export and import electricity respectively. Even though the reduction rates were not significant, the daily export electricity cut was as high as 7.4kWh, where the actual impact on the import electricity was 5.9kWh per day contributing to the highest energy reduction. This occurred due to the oversized PV system in conjunction with low load demand, especially during hours with high PV production as illustrated in Figure 16. Also, it can be observed that battery charging profile dropped significantly before the PV yield peaked, noting that the battery charge level was almost high, therefore any additional PV yield was gradually exported to the utility grid.

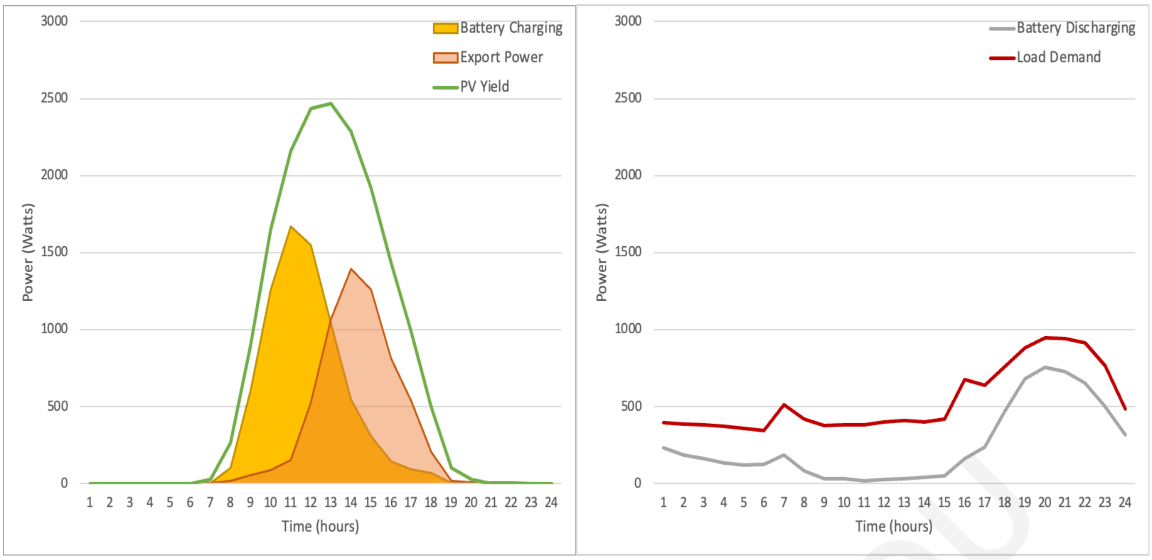


***Figure 16**. Average daily energy balance of Pilot 1.*

The battery SoC was also investigated to assess the sizing methodology and moreover the selected capacity of the coupled PV-BES system. To this extend, the maximum observed SoC level was extracted from the datasets for each hour of the reference year. This is illustrated in Figure 17 where the SoC levels represent the usable battery capacity which was 9.3kWh. The SoC patterns revealed a uniform BES usage profile for all pilots where the maximum SoC level was reached during the afternoon hours due to surplus energy storage, where it dropped down until the early morning hours as energy was dispatched from the battery to the residential load. It can be noted that the SoC levels reached the practical maximum level of 100% - fully charged battery, only for a few hours of the day meaning that the selected battery sizing fits the energy profile of the selected pilots. It is worth noting that the SoC pattern of Pilot 1 differs from the other systems pattern. More specifically, the maximum point was reached midday and remained constant for a prolonged amount of time. Further to this, SoC level difference throughout a typical day was 35% of the total usable battery capacity, in contrast to other systems that reached lower SoC levels. This is justified by the oversized PV system capacity and the reduced energy demands, meaning that the BES capacity can be increased to further reduce the amount of energy that was spilled to the grid. On the contrary, the BES capacity derived by the sizing methodology, fits the surplus energy profiles of Pilots 2, 3 and 4. The remaining surplus energy, which is between 0.2kWh and 0.9kWh, is very small and upgrading the BES capacity will not bring any reasonable improvement either to the SCR or the SoC profile.

Finally, the SCR is summarized in

Table 6 over the entire reference period where a comparison of the self-consumed energy was examined before and after integrating the coupled PV-BES system. The SCR performed best with the PV-BES system, having an average increase of approximately 40%. In addition, the maximum reached SoC was 96%, meaning that almost all the PV yield throughout the reference year was locally consumed by the residential load, improving the self-sufficiency of the residential premises.

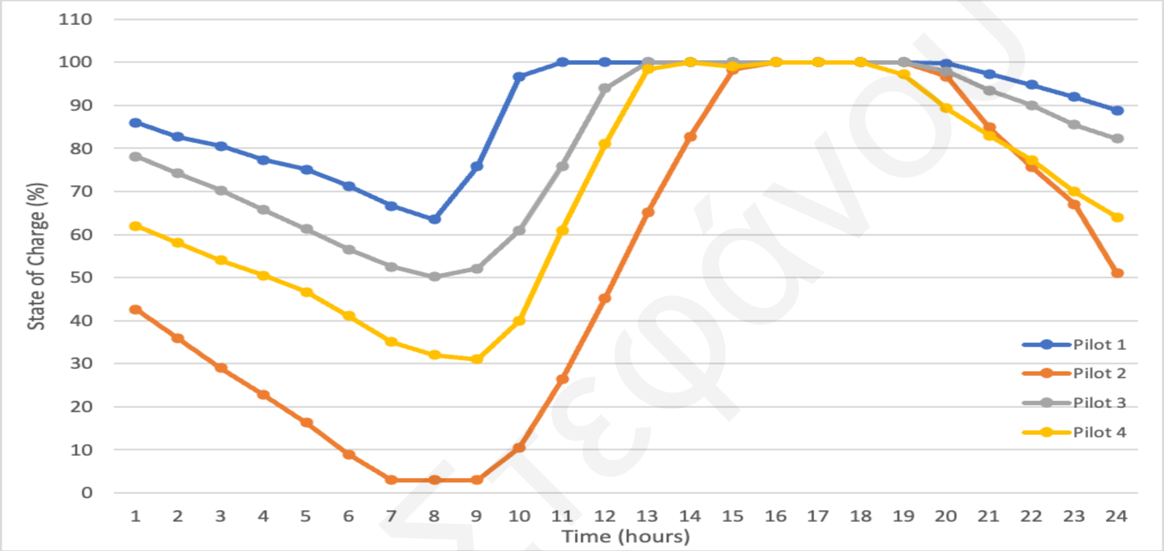


Figure 17. *Peak hourly SoC level of the pilots.*

Table 6. *Annual SCR comparison before and after BES integration.*

	Annual PV Yield	**PV System only**		**PV-BES System**	
		Annual Self-Consumption	SCR_{PV}	Annual Self-Consumption	SCR_{BES}
Pilot 1	6253 KWh	1325 KWh	21%	4020 KWh	64%
Pilot 2	4773 KWh	2873 KWh	61%	4580 KWh	96%
Pilot 3	4592 KWh	2042 KWh	44%	4289 KWh	93%
Pilot 4	3870 KWh	2358 KWh	54%	3602 KWh	93%

5. Conclusions and Future Work

The primary scope of this thesis is to group pilot users into the three primary clusters, and also verify the sizing methodology proposed in this study. To this extend, the annual energy datasets taken from smart meters were used to characterize the import energy profiles of typical prosumers in Cyprus. Based on the k-means technique, a clustering methodology was used to determine the import energy clusters, which provided information about the daily import energy levels as well as seasonal variations on the load patterns. The methodology concluded to three energy clusters, ranking Cluster 3 the most dominant group with 34 prosumers in total, representing a typical import profile with small seasonal deviations and an average daily import energy of 14.5kWh. With 20 prosumers in total, Cluster 1 followed, representing users that contributed to import needs as low as 11.9kWh in comparison to Cluster 1 which constituted of 11 users and the highest import energy level of 17.4kWh per day over the test year.

Further to this, the power and energy datasets extracted for each cluster were used for the development of a battery energy storage (BES) sizing procedure. By examining the system capacity first, the analysis revealed that grid balancing was not possible. More specifically, the relatively high import energy levels of the participating premises could not be met completely by the surplus PV electricity and, hence by the BES storage. In particular, the surplus PV electricity for Cluster 1 reached up to 8.2kWh per day and for Cluster 2 and Cluster 3 was 6.8kWh and 8.0kWh respectively. Similarly, a statistical analysis was performed on a seasonal basis for the power dimensioning of the BES system. The analysis revealed similar power behavior for Cluster 1 and Cluster 3 with the average power to be 1.5kW and 1.8kW, with the power rate for Cluster 2 to be 2.2kW. Based on the highest observations of the three dominant prosumer clusters a system of 2.2kW/8.2kWh was the desired BTM storage that could fit in typical residential premises in Cyprus.

Next, AC-Coupled BES systems closely matching to the desired BES were installed at four residential pilot systems with existing PV systems, forming a behind-the-meter (BTM) solution. The annual energy datasets collected revealed a significant decrease between 4.1kWh and 7.4kWh on the daily export electricity of the pilots, which was locally stored to the BES system. This also affected the import energy levels which showed a considerable reduction of 3.4-5.9kWh, representing the energy being dispatched from the

BES system. The performance of the AC-Coupled BTM storage system was evaluated by comparing the self-consumption ratio (SCR) before and after the integration of the BES system. In particular, the annual SCR of the pilots has been significantly improved, reaching up to 96% compared to the level levels before the BTM storage integration. This verified the sizing methodology proposed in this study as the selected BES system dimensioning fitted the energy patterns of residential loads in Cyprus. In fact, the surplus PV electricity was completely utilized through the BES system, showing that surplus energy was identical to the selected BES capacity. With regards to the annual SCR of Pilot 1, it remained as low as 64% compared to 21% before BES integration. This occurred due to the large PV system size compared to the extremely low energy demand of the premise. In fact, if the BES capacity of Pilot 1 was increased by 6.1kWh, then grid balance could be achieved.

Finally, the option of allocating the BES units to a larger centralized in front-of-the-meter (FTM) storage instead of small distributed units can be considered as a future work of this project. To validate the scenario of FTM storage, a 30kW/50kWh centralized storage unit was installed at the LV distribution feeder that supplies the four residential pilots. This brings new research topics such as the comparison of BTM and FTM storage in terms of system performance and energy losses. Also, BES cost can be optimized when centralized and distributed coordination is examined. Finally, the potential of providing ancillary grid services can also be investigated in high PV penetration scenarios.

References

[1] G. A. Barzegkar-Ntovom *et al.*, “Assessing the viability of battery energy storage systems coupled with photovoltaics under a pure self-consumption scheme,” *Renew. Energy*, vol. 152, no. 2020, pp. 1302–1309, 2020, doi: 10.1016/j.renene.2020.01.061.

[2] European_Commission, “The Commission’s Energy Roadmap 2050,” 2011. http://europa.eu/rapid/press-release_MEMO-11-914_en.htm

[3] European_Commission, “Energy storage – the role of electricity,” Brussels, 2017.

[4] European_Commission, “Communication on Accelerating Clean Energy Innovation,” 2016. [Online]. Available: http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v6_0.pdf

[5] H. Yang *et al.*, “The battery storage management and its control strategies for power system with photovoltaic generation,” in *Emerging Trends in Energy Storage Systems and Industrial Applications*, Prabhansu and N. Kumar, Eds. Academic Press, 2023. doi: https://doi.org/10.1016/B978-0-323-90521-3.00013-2.

[6] N. Shaukat *et al.*, “A survey on electric vehicle transportation within smart grid system,” *Renew. Sustain. Energy Rev.*, vol. 81, no. February 2016, pp. 1329–1349, 2018, doi: 10.1016/j.rser.2017.05.092.

[7] “European Commission: Energy Storage, 2016.” [Online]. Available: https://ec.europa.eu/energy/en/topics/technology-and-innovation/energy- storage

[8] Cyprus-TSO, “Penetration of Renewable Energy Sources (RES) into the Cyprus electrical system,” Nicosia, 2022.

[9] C. Kost, S. Shammugam, V. Fluri, D. Peper, A. D. Memar, and T. Schlegel, “Levelized Cost of Electricity- Renewable Energy Technologies June 2021,” no. June, pp. 1–45, 2021, [Online]. Available: www.ise.fraunhofer.de%0ADirectors

[10] I. MinistryofEnergy,Commerce, “Solar Energy for all,” 2021.

[11] A. Salah Saidi, “Impact of grid-tied photovoltaic systems on voltage stability of tunisian distribution networks using dynamic reactive power control,” *Ain Shams Engineering Journal*, vol. 13, no. 2. 2022. doi: 10.1016/j.asej.2021.06.023.

[12] T. O. Olowu, A. Sundararajan, M. Moghaddami, and A. I. Sarwat, “Future Challenges and Mitigation Methods for High Photovoltaic Penetration: A Survey,” *Energies*, vol. 11, no. 7, 2018, doi: 10.3390/en11071782.

[13] Electricity Authority of Cyprus (EAC), “Disconnection of PV systems connected to the distribution system.” https://www.eac.com.cy/EL/EAC/NewsAndAnnouncements/Pages/aposindesifotovoltaikon.aspx (accessed Jan. 25, 2023).

[14] M. H. Coddington and N. R. E. L. (U.S.), *High-Penetration Photovoltaic Standards and Codes Workshop: Workshop Proceedings : Denver, Colorado, May 20, 2010*. National Renewable Energy Laboratory, 2010. [Online]. Available: https://books.google.com.cy/books?id=usH2ugEACAAJ

[15] A. Moghadasi, A. Sargolzaei, A. Khalilnejad, M. Moghaddami, and A. Sarwat, “Model predictive power control approach for three-phase single-stage grid-tied PV module-integrated converter,” in *2016 IEEE Industry Applications Society Annual Meeting*, Oct. 2016, pp. 1–6. doi: 10.1109/IAS.2016.7731868.

[16] S. Panda *et al.*, “Residential Demand Side Management model, optimization and future perspective: A review,” *Energy Reports*, vol. 8, pp. 3727–3766, 2022, doi: https://doi.org/10.1016/j.egyr.2022.02.300.

[17] N. S. Wade, P. C. Taylor, P. D. Lang, and P. R. Jones, “Evaluating the benefits of an electrical energy storage system in a future smart grid,” *Energy Policy*, vol. 38, no. 11, pp. 7180–7188, 2010, doi: https://doi.org/10.1016/j.enpol.2010.07.045.

[18] J. Weniger, T. Tjaden, and V. Quaschning, “Sizing of Residential PV Battery Systems,” *Energy Procedia*, vol. 46, pp. 78–87, Jan. 2014, doi: 10.1016/J.EGYPRO.2014.01.160.

[19] S. Ouédraogo, G. A. Faggianelli, G. Notton, J. L. Duchaud, and C. Voyant, “Impact of electricity tariffs and energy management strategies on PV/Battery microgrid performances,” *Renew. Energy*, vol. 199, no. August, pp. 816–825, 2022, doi: 10.1016/j.renene.2022.09.042.

[20] A. Sani Hassan, L. Cipcigan, and N. Jenkins, “Optimal battery storage operation for PV systems with tariff incentives,” *Appl. Energy*, vol. 203, pp. 422–441, 2017, doi: 10.1016/j.apenergy.2017.06.043.

[21] Y. Wu, Z. Liu, B. Li, J. Liu, and L. Zhang, “Energy management strategy and optimal battery capacity for flexible PV-battery system under time-of-use tariff,” *Renew. Energy*, vol. 200, no. July, pp. 558–570, 2022, doi: 10.1016/j.renene.2022.09.118.

[22] A. Pena-Bello, E. Barbour, M. C. Gonzalez, M. K. Patel, and D. Parra, “Optimized PV-coupled battery systems for combining applications: Impact of battery technology and geography,” *Renew. Sustain. Energy Rev.*, vol. 112, no. May, pp. 978–990, 2019, doi: 10.1016/j.rser.2019.06.003.

[23] E. Zarate-Perez and R. Sebastián, “Autonomy evaluation model for a photovoltaic residential microgrid with a battery storage system,” *Energy Reports*, vol. 8, no. May, pp. 653–664, 2022, doi: 10.1016/j.egyr.2022.07.085.

[24] Q. Chen, Z. Kuang, X. Liu, and T. Zhang, “Energy storage to solve the diurnal, weekly, and seasonal mismatch and achieve zero-carbon electricity consumption in buildings,” *Appl. Energy*, vol. 312, no. February, p. 118744, 2022, doi: 10.1016/j.apenergy.2022.118744.

[25] E. O. Ogunniyi and H. C. V. Z. Pienaar, “Overview of battery energy storage system advancement for renewable (photovoltaic) energy applications,” *Proc. 25th Conf. Domest. Use Energy, DUE 2017*, pp. 233–239, 2017, doi: 10.23919/DUE.2017.7931849.

[26] Z. Šimić, G. Knežević, D. Topić, and D. Pelin, “Battery energy storage technologies overview,” *Int. J. Electr. Comput. Eng. Syst.*, vol. 12, no. 1, pp. 53–65, 2021, doi: 10.32985/IJECES.12.1.6.

[27] S. Koohi-Fayegh and M. A. Rosen, “A review of energy storage types, applications and recent developments,” *J. Energy Storage*, vol. 27, no. July 2019, p. 101047, 2020, doi: 10.1016/j.est.2019.101047.

[28] M. Vetter and L. Rohr, *Lithium-Ion Batteries for Storage of Renewable Energies and Electric Grid Backup*. Elsevier, 2014. doi: 10.1016/B978-0-444-59513-3.00013-3.

[29] Y. Zhang, T. Ma, and H. Yang, “Grid-connected photovoltaic battery systems: A comprehensive review and perspectives,” *Appl. Energy*, vol. 328, no. July, p. 120182, 2022, doi: 10.1016/j.apenergy.2022.120182.

[30] M. M. Rana, M. Uddin, M. R. Sarkar, G. M. Shafiullah, H. Mo, and M. Atef, “A review on hybrid photovoltaic – Battery energy storage system: Current status, challenges, and future directions,” *Journal of Energy Storage*, vol. 51. 2022. doi: 10.1016/j.est.2022.104597.

[31] N. Zhang, D. Sutanto, and K. M. Muttaqi, “A review of topologies of three-port DC-DC converters for the integration of renewable energy and energy storage system,” *Renew. Sustain. Energy Rev.*, vol. 56, pp. 388–401, 2016, doi: 10.1016/j.rser.2015.11.079.

[32] S. Afxentis *et al.*, “Promotion of Higher Penetration of Distributed PV Through Storage for All (StoRES),” in *INCREaSE*, Cham: Springer International Publishing, 2018, pp. 479–488. doi: 10.1007/978-3-319-70272-8_37.

[33] S. Afxentis and M. Florides et al, “Guidelines for the Design of Residential and Community Level Storage Systems Combined with Photovoltaics (PV),” 2017.

[34] W. M. Sarhan, A. N. Alkhateeb, K. D. Omran, and F. H. Hussein, “Effect of temperature on the efficiency of the thermal cell,” *Asian J. Chem.*, vol. 18, no. 2, pp. 982–990, 2006.

[35] G. Walker, “The dynamics of energy demand: Change, rhythm and synchronicity,” *Energy Res. Soc. Sci.*, vol. 1, pp. 49–55, Mar. 2014, doi: 10.1016/j.erss.2014.03.012.

[36] S. Afxentis, M. Florides, S. Theocharides, V. Venizelou, and G. E. Georghiou, “Residential Battery Storage Sizing Based on Daily PV Production and Consumption Load Profile Characterization,” *35th Eur. Photovolt. Sol. Energy Conf. Exhib.*, no. Lv, 2018, doi: 10.4229/35thEUPVSEC20182018-6EO.2.3.

[37] P. Galeano and D. Pena, “Multivariate Analysis in Vector Time Series,” *Resenhas do Inst. Matemática e Estatística da Univ. São Paulo*, vol. 4, no. 4, pp. 383–403, 2000.

[38] P. (University of A. C. Montero and J. A. (University of C. Vilar, “TSclust: An R Package for Time Series Clustering,” *JSS J. Stat. Softw.*, vol. 62, no. 1, pp. 1–43, 2014.

[39] A. L. Klingler and L. Teichtmann, “Impacts of a forecast-based operation strategy for grid-connected PV storage systems on profitability and the energy system,” *Sol. Energy*, vol. 158, no. June, pp. 861–868, 2017, doi: 10.1016/j.solener.2017.10.052.

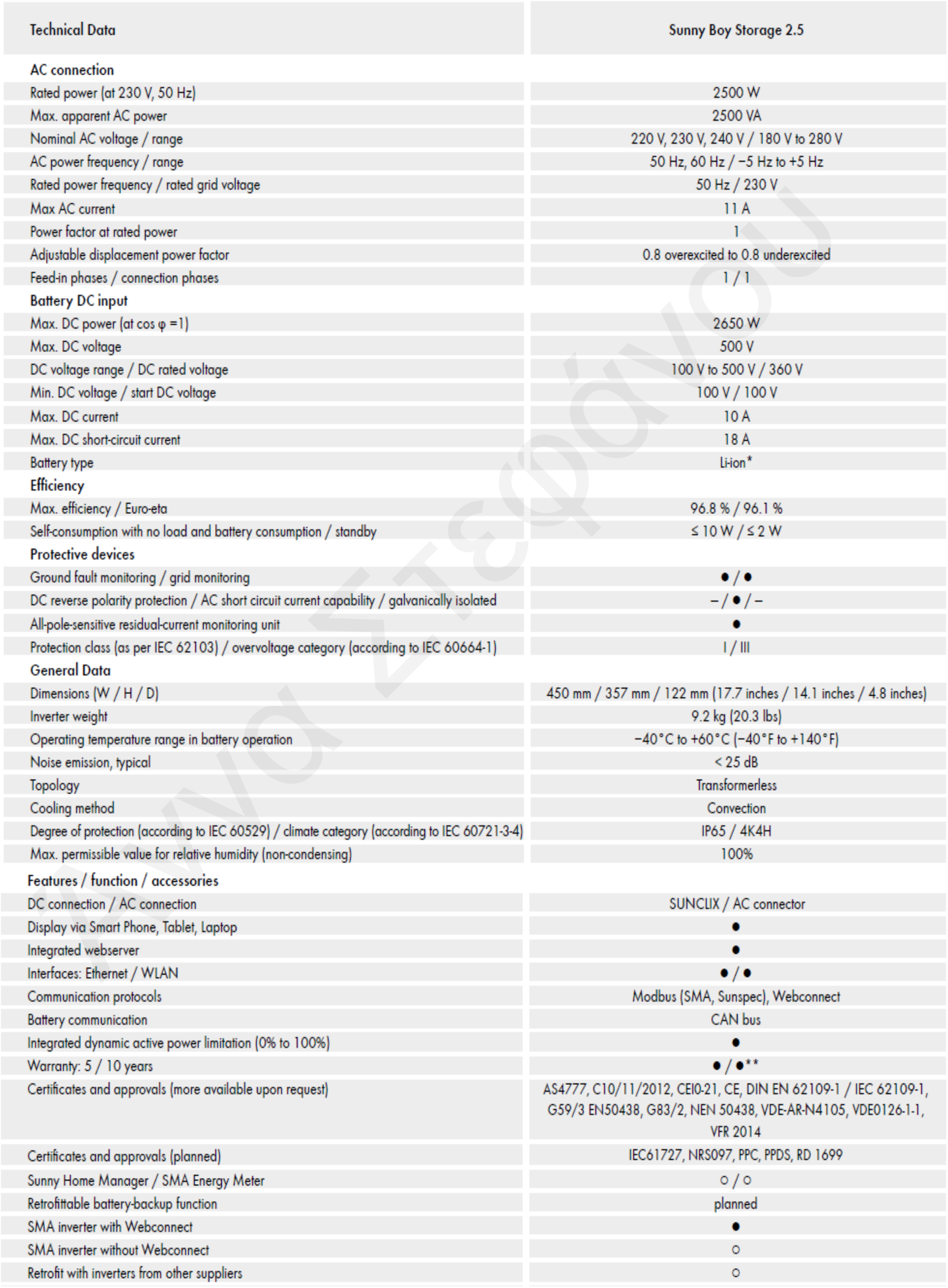
[40] R. L. Fares and M. E. Webber, “The impacts of storing solar energy in the home to reduce reliance on the utility,” *Nat. Energy*, vol. 2, p. 17001, Jan. 2017, [Online]. Available: https://doi.org/10.1038/nenergy.2017.1

[41] G. Makrides, B. Zinsser, M. Norton, G. E. Georghiou, M. Schubert, and J. H. Werner, “Potential of photovoltaic systems in countries with high solar irradiation,” *Renew. Sustain. Energy Rev.*, vol. 14, no. 2, pp. 754–762, Feb. 2010, doi: 10.1016/j.rser.2009.07.021.

[42] R. A. Agathokleous and S. A. Kalogirou, “PV roofs as the first step towards 100% RES electricity production for Mediterranean islands: The case of Cyprus,” *Smart Energy*, vol. 4, p. 100053, 2021, doi: 10.1016/j.segy.2021.100053.

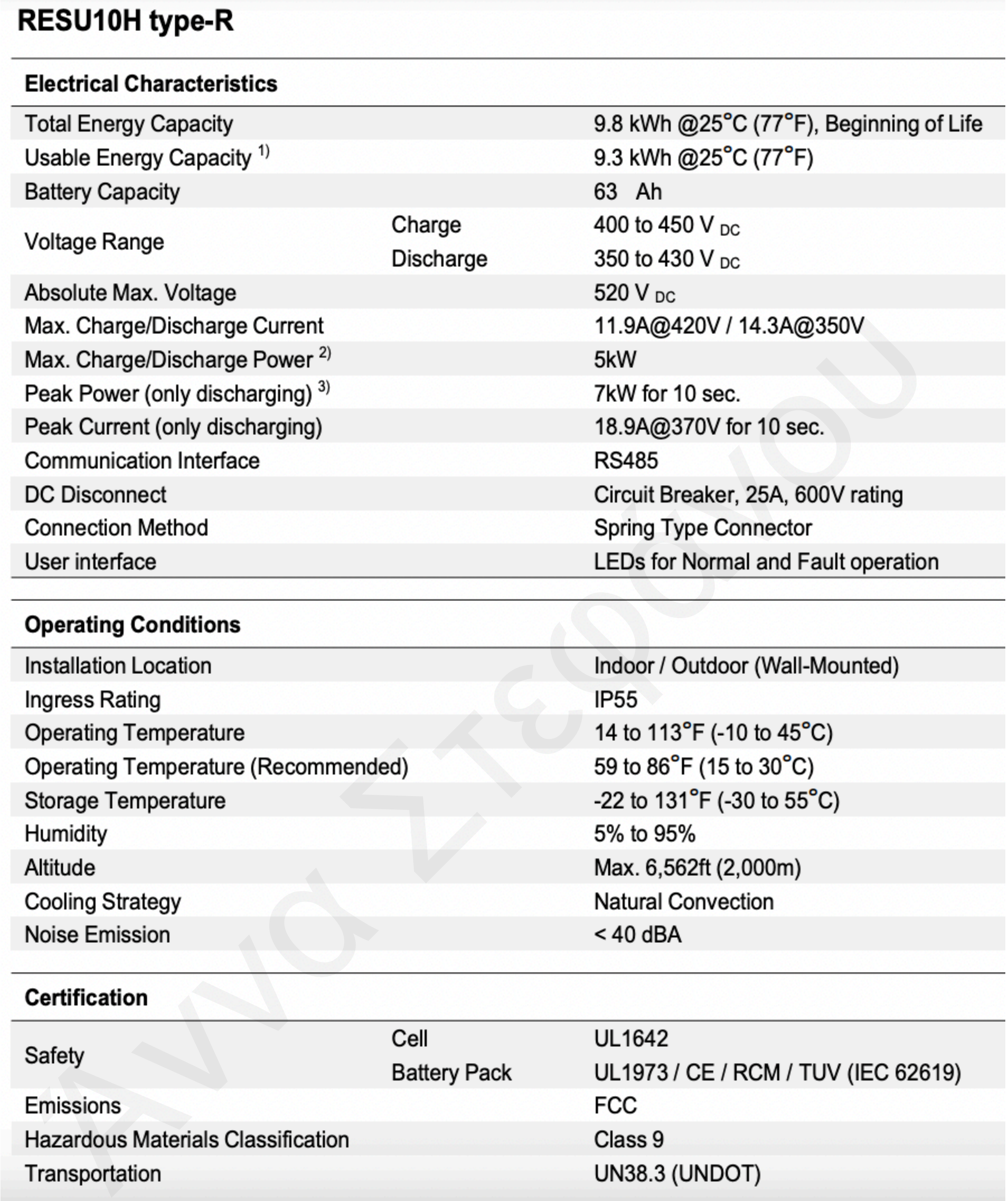
Appendix

Power Converter Specifications



Technical Data	Sunny Boy Storage 2.5
AC connection	
Rated power (at 230 V, 50 Hz)	2500 W
Max. apparent AC power	2500 VA
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V to 280 V
AC power frequency / range	50 Hz, 60 Hz / −5 Hz to +5 Hz
Rated power frequency / rated grid voltage	50 Hz / 230 V
Max AC current	11 A
Power factor at rated power	1
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited
Feed-in phases / connection phases	1 / 1
Battery DC input	
Max. DC power (at cos φ =1)	2650 W
Max. DC voltage	500 V
DC voltage range / DC rated voltage	100 V to 500 V / 360 V
Min. DC voltage / start DC voltage	100 V / 100 V
Max. DC current	10 A
Max. DC short-circuit current	18 A
Battery type	Li-ion*
Efficiency	
Max. efficiency / Euro-eta	96.8 % / 96.1 %
Self-consumption with no load and battery consumption / standby	≤ 10 W / ≤ 2 W
Protective devices	
Ground fault monitoring / grid monitoring	● / ●
DC reverse polarity protection / AC short circuit current capability / galvanically isolated	– / ● / –
All-pole-sensitive residual-current monitoring unit	●
Protection class (as per IEC 62103) / overvoltage category (according to IEC 60664-1)	I / III
General Data	
Dimensions (W / H / D)	450 mm / 357 mm / 122 mm (17.7 inches / 14.1 inches / 4.8 inches)
Inverter weight	9.2 kg (20.3 lbs)
Operating temperature range in battery operation	−40 °C to +60 °C (−40 °F to +140 °F)
Noise emission, typical	< 25 dB
Topology	Transformerless
Cooling method	Convection
Degree of protection (according to IEC 60529) / climate category (according to IEC 60721-3-4)	IP65 / 4K4H
Max. permissible value for relative humidity (non-condensing)	100%
Features / function / accessories	
DC connection / AC connection	SUNCLIX / AC connector
Display via Smart Phone, Tablet, Laptop	●
Integrated webserver	●
Interfaces: Ethernet / WLAN	● / ●
Communication protocols	Modbus (SMA, Sunspec), Webconnect
Battery communication	CAN bus
Integrated dynamic active power limitation (0% to 100%)	●
Warranty: 5 / 10 years	● / ●**
Certificates and approvals (more available upon request)	AS4777, C10/11/2012, CEI0-21, CE, DIN EN 62109-1 / IEC 62109-1, G59/3 EN50438, G83/2, NEN 50438, VDE-AR-N4105, VDE0126-1-1, VFR 2014
Certificates and approvals (planned)	IEC61727, NRS097, PPC, PPDS, RD 1699
Sunny Home Manager / SMA Energy Meter	○ / ○
Retrofittable battery-backup function	planned
SMA inverter with Webconnect	●
SMA inverter without Webconnect	○
Retrofit with inverters from other suppliers	○

Battery Unit Specifications



RESU10H type-R

Electrical Characteristics		
Total Energy Capacity		9.8 kWh @25°C (77°F), Beginning of Life
Usable Energy Capacity [1]		9.3 kWh @25°C (77°F)
Battery Capacity		63 Ah
Voltage Range	Charge	400 to 450 V_{DC}
	Discharge	350 to 430 V_{DC}
Absolute Max. Voltage		520 V_{DC}
Max. Charge/Discharge Current		11.9A@420V / 14.3A@350V
Max. Charge/Discharge Power [2]		5kW
Peak Power (only discharging) [3]		7kW for 10 sec.
Peak Current (only discharging)		18.9A@370V for 10 sec.
Communication Interface		RS485
DC Disconnect		Circuit Breaker, 25A, 600V rating
Connection Method		Spring Type Connector
User interface		LEDs for Normal and Fault operation

Operating Conditions	
Installation Location	Indoor / Outdoor (Wall-Mounted)
Ingress Rating	IP55
Operating Temperature	14 to 113°F (-10 to 45°C)
Operating Temperature (Recommended)	59 to 86°F (15 to 30°C)
Storage Temperature	-22 to 131°F (-30 to 55°C)
Humidity	5% to 95%
Altitude	Max. 6,562ft (2,000m)
Cooling Strategy	Natural Convection
Noise Emission	< 40 dBA

Certification		
Safety	Cell	UL1642
	Battery Pack	UL1973 / CE / RCM / TUV (IEC 62619)
Emissions		FCC
Hazardous Materials Classification		Class 9
Transportation		UN38.3 (UNDOT)

Residential Pilot Sites:

Pilot 1

Pilot 2

Pilot 3

Pilot 4