INTERNATIONAL
HELLENIC
UNIVERSITY

Investigation of Hybrid Power Stations implementation in Greek islands not connected to the national grid

Koltsios Stavros

SID: 3304190004

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Building Design

JANUARY 2021
THESSALONIKI – GREECE

Investigation of Hybrid Power Stations implementation in Greek islands not connected to the national grid

Koltsios Stavros

SID: 3304190004

Supervisor:	Dr. Martinopoulos Georgios
Supervising Committee Members:	Assoc. Prof. Name Surname Assist. Prof. Name Surname

SCHOOL OF SCIENCE & TECHNOLOGY
A thesis submitted for the degree of
Master of Science (MSc) in Energy Building Design

JANUARY 2021
THESSALONIKI – GREECE

Abstract

The scope of this thesis is to investigate the viability of implementing Hybrid Power Station (HPS) facilities in the autonomous electrical systems of Non-Interconnected Greek islands. The term HPS refers to a combined station that consist of a renewable energy power source and an energy storage facility. The first step consists of the research for all the available technologies for utility scale energy storage systems that can be coupled with electric generation stations from renewable sources and installed on Greek islands. The selection of the most appropriate solutions for power production and storage will be based on the maturity of each technology, energy needs of the specific location, morphology of the Greek islands and the financial parameters that affect investments in this type of projects.

The next step is to simulate the operation of the HPS in the system of a non-interconnected island grid. The development of algorithms for the hourly dispatch of the HPS is based on the Greek regulatory operational framework for Non-Interconnected islands. The algorithms have been developed in the of MATLAB software. From this investigatin are produced the the benefits from the operation of an HPS to the operation of the islands electric production system. Also, the simulation of HPS configurations provide the opportunity to compare HPS with different storage systems (batteries and Pumped Hydro) in order to find the most suitable solution.

Finally, in order to evaluate financial viability of HPS systems at not interconnected islands, a pricing policy is proposed, which is the basis for the calculation of the revenues generated from providing energy and ancillary services to isolated island electrical systems. In order to find the best approach for the development of an HPS station, a comparison between the previously selected HPS systems is conducted, with the units sized at the same capacity. Results both the HPS operation as well as for the operation of the island's electrical system are presented in order to prove which HPS type is more beneficial for the island operation and which is the investment option is more profitable.

Koltsios Stavros
15/1/2021

Contents

Abbreviations

RES	Renewable Energy Sources
WF	Wind Farms
PV	Photovoltaic
APGS	Autonomous Power Generation Stations
NII	Non-Interconnected Islands
PHS	Pumped Hydro Storage
HPS	Hybrid Power Station
EMS	Energy Management System
O&M	Operation and Maintenance
CF	Capacity Factor
APS	Autonomous Power Stations
APGS	Autonomous Power Generation Stations
SMP	System Marginal Price
AVC	Average Variable Cost
AEPS	Autonomous EPS
SHV	Super High Voltage
HV	High Voltage
ESS	Energy Storage Systems
BESS	Battery Energy Storage Systems
LMP	Locational Marginal Price
AC	Alternating Current
CAES	Compressed Air Energy Storage
VRB	Vanadium Redox Batteries
SOC	State of Charge

DC	Direct Current
AC	Alternating Current
DoD	Depth of Discharge
UPS	Uninterruptible Power Supply
VRLA	Valve Regulated Batteries
FBESS	Flow Battery Energy Storage System
PHES	Pumped Hydroelectric Storage
ISO	Island System Operator
DGDS	Daily Generation Dispatch Schedule

1 Introduction

The need for transformation in the electric production sector and shift to renewable energy sources (RES) has been increased in the past two decades. European Union has set as a goal to zero greenhouse gas emissions by 2050 and sustain this level for the second half of this century. Especially Greece has set as a goal to increase the share of RES in the electrical energy consumption mix at 60% by the end of 2030 [1]. Currently, the use of fossil fuels prevails in the Greek electricity production sector (Figure 1), where lignite (with red colour) and natural gas (with orange color) are the two major energy sources, while the share of oil is considered too small [2]. Even though RES (including hydro generation) have a significant portion in the energy mix, there is much more room for RES exploitation as indicated by the country's high solar and wind potential [3]. Increasing the capacity of RES stations is the steppingstone to achieve the above national and European goals.

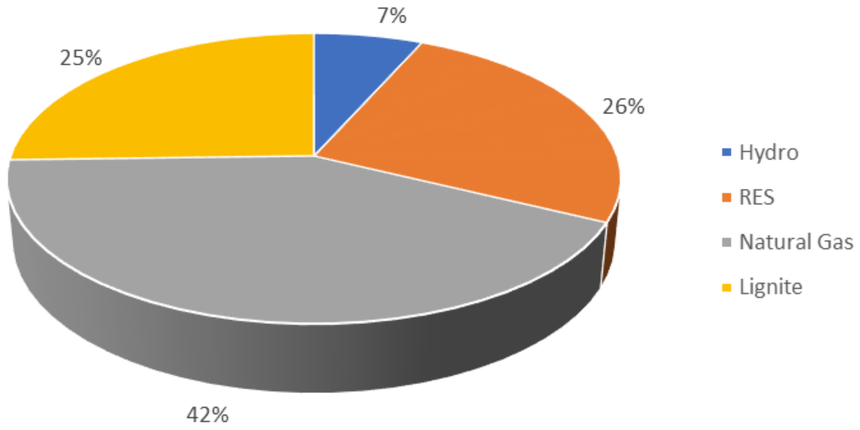


Figure 1: Percentage of fossil fuels in the Greek annual electricity production [2]

Precondition for implementing large amounts of RES units, is the existence of a robust electric grid infrastructure [3]. The National Greek electricity Grid can be divided in two main categories. Firstly, on the mainland exists a large interconnected system that includes transfer and distribution network. There are also grid lines that connect the west Greek islands (Corfu, Lefkada, Kefalonia, Zakynthos) to the mainland. Furthermore, the systems is interconnected to neighbor countries Bulgaria, Albania, FYROM and Italy that establish an even more robust system capable to supply energy in a reliable and uninterrupted way [4]. On the other hand, many Greek islands' isolated location deters their connection to the mainland grid due to various technical and financial problems. The small size of their grids can induce several problems to their energy production system, at the same time energy production from installed RES is limited despite the large RES potential of these locations [3].

In the Greek area exist 124 islands and 36 of them are not included into the electric grid of the National Interconnected System of Electric Energy Transmission [5]. The electrification of Non-Interconnected Islands (NII) is based primarily on thermal power stations and on a smaller percentage on RES, mainly wind farms (WF) and photovoltaic (PV) power stations. In most cases the quality of electricity is low and the production cost is relatively high, in certain islands even exceeds 1€/kWh, especially for the smaller islands [6]. The installed capacity of conventional and RES units on each island is proportional to the island size and the number of its inhabitants. Although the island's energy profile parameters, such as total and peak energy demand, are not defined only by the latter two characteristics. One equally important parameter is the seasonality of the load, the intense variations of the local demand are largely owed to the that Greek islands are popular tourist destinations in the summer period and have low number of inhabitants during the winter [7]. The summer peak load demand may be one order of magnitude higher than the minimum winter electricity consumption [6].

So far, the supply of electricity to NII has relied on national policies and economic incentives that oblige citizens both in mainland and islands pay the same cost for electricity. A regular financial transfer has, thus, been placed to cover the higher costs of electricity generation in the islands. Islands' electricity systems rely heavily on oil- and diesel-based electricity stations, for which the operation fuel needs to be purchased and transported, with a significant economic burden for the central government budget. This significant cost is subsidized and shared by all mainland consumers through a levy on electricity bills. Such a solution was viable as long as the cost of oil was low and alternative solutions were either at an early stage of technological maturity or too expensive. However, this is not the case anymore. The fluctuating and increased cost of fuel is even more expensive on islands, due to the expensive transport involved. Considering the additional local pollution that this transfer creates to these tourist destinations and the future costs of greenhouse gas emissions' taxation, it becomes clear that the current status of islands' electrification is not sustainable [7].

It is clear that in order to lower the operation cost of NII it is necessary to expand the installation of RES units. One issue with renewable energy sources is the stochastic nature of their availability. The production of electricity from RES does not coincide with the electrical demand of the population, for example as far as solar power is considered, the sun sets as the electricity demand increases when people come home from work. Furthermore, power generation from RES presents various fluctuations and a stochastic character, because it highly dependent from weather parameters (sunshine intensity, air velocity). Since conventional units are called to bridge the gap between RES production and load demand, several operational restrictions limit the expansion of RES units [3]. Hence, energy transformation of island's electrical systems should reassure the energy safety and power adequacy for the systems and in the same time align with the national goals [2].

In order to solve the problem of increasing RES capacity in Greek islands, two main strategies have been developed. The first one includes the connection of the NII to the mainland grid. In this way, the island will be a part of a robust electricity system and will be able to fully utilize their RES potential, also benefiting the mainland grid. This issue was addressed in the main Ionian Islands through interconnections to the mainland Greek grid between 1960 and 1980. In April 2018 the first phase of the interconnection project of the Cyclades, an island group of the Aegean Sea, to the main grid was completed. The project was signed in 2014 and interconnected four main islands (Syros, Mykonos, Tinos, Paros) to the central electrical grid [7].The interconnection of Crete is currently under construction, while the are plans on interconnecting all the major islands in central and north-east Aegean see (Figure 2) [8]. Despite the ongoing interconnection projects, the majority of the Aegean Sea islands will continue to produce electricity in a business-as-usual manner. In the short- and medium-term it is not expected that interconnection to the main grid will be a universal solution for all islands [7].

Figure 2: Greek islands interconnection map [8]

The second strategy issues the development of energy storage facilities on each NII, according to the specific need of each island system [7]. The introduction of energy storage is considered as the most effective means to resolve obstacles in order to significantly increase RES penetration levels in electric power systems, especially in the case of NII [9]. Using this approach, RES production will be able to supply enough energy for the island and store the excess amount for later use or when the load demand rises to its peak values. In the current market exists a variety of energy storage options, although one should define several operation and economical parameters before selecting the appropriate type for each application. Despite the opportunity offered by the energy storage systems to increased energy stability and reliability of the intermittent energy sources, there were only four energy storage technologies (sodium–sulphur batteries, pumped hydro energy storage, compressed air energy storage, and thermal storage) with a globally installed capacity exceeding 100 MW [10]. Recent studies have shown that PHS and battery technologies are more suitable for the case of Aegean islands, thus this dissertation will be mainly focused on these two storage types. Battery storage can be more effective for small size islands, while for electrical power systems with size larges that a few MW or more, pumped hydro storage (PHS) is considered the technically more mature and economically viable alternative. Nevertheless, storage technologies like fuel cells and flow batteries may suggest promising future solutions, since their cost is at the moment higher than the traditional systems [9].

Up to now, two pilot HPS projects have been implemented on the Greek islands of Ikaria and Tilos. These stations have been used as test beds to implement the operating policy for the stations and the island systems and evaluate the benefits for the energy equilibrium of the islands. Their main characteristics of each application are briefly presented below.

Ikaria HPS consists of three distinct water reservoirs which are located in sufficient altitude differences (Figure 3). Pezi reservoir is currently used for irrigation and water supply, excess water from the reservoir is exploited for energy production. The two lower reservoirs are only used for pump storage purposes. Apart from hydroelectric energy generation, via exploitation of excess water from the upper reservoir, Ikaria HPS also uses three wind turbines of 900kW each, in order to generate energy. The operation of the station is estimated to produce 9,8 GWh/year, covering a large portion of the annually energy demand of the island, mainly during winter months. Since the island's oil fired units operation is minimized, there is a vast reduction of CO_2 emissions by 13.000 tons annually [11], [12].

From operation of the HPs have been concluded the following facts. Pumped hydro technology requires a complex and long-lasting development procedure. Furthermore, long distances between the storage reservoirs can create uncertainties at the amounts of energy production. Finally, HPS hydro-turbines must have the ability to provide ancillary services to the grid. [64]

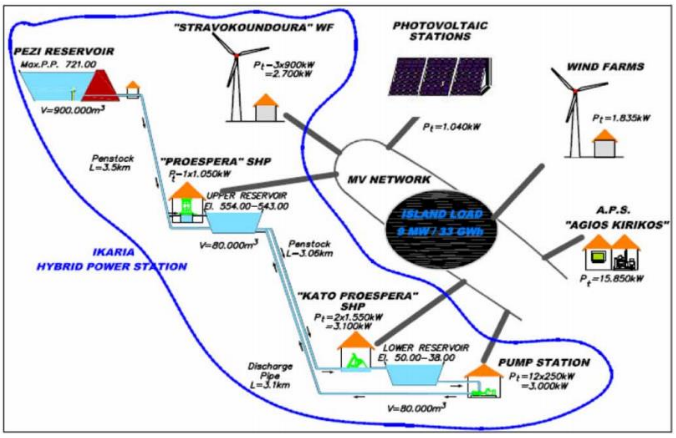


Figure 3: Ikaria HPS schematic diagram [11]

Tilos HPS utilizes a different storage system, which consists of nickel batteries with rated power of 800kW and with a rated capacity of 2.800MWh. The energy production is provided by two renewable energy sources, an 800kW wind turbine in combination with a photovoltaic station of 160kW. Apart from the HPS, smart meters and demand side management devices have also been installed in the residential sector and other, central loads of Tilos island [22]. Moreover, a smart energy management system (EMS) has been developed, that coordinates the operation of the various components to achieve the highest possible electricity autonomy and balance between intermittent RES electricity production and electricity demand, with the support of battery storage and demand side management at the same time [13].

After the first year of operation the main conclusion is that the size of the HPS is able to cover the island’s energy needs under certain conditions. Furthermore, it is necessary for the new HPS stations to have the ability of frequency and voltage regulation, black start ability and further technical characteristics to back up the system without the need of a thermal unit to operate at the same time [64].

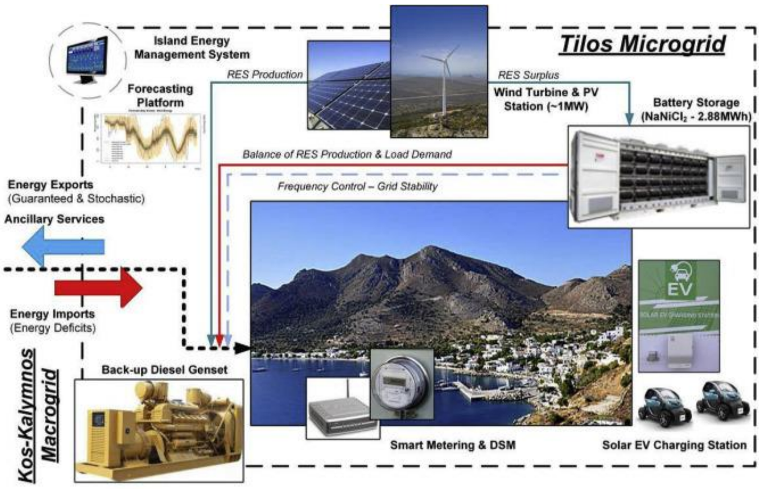


Figure 4:Tilos Microgrid schematic diagram [13]

2 Energy Production, Distribution and Storage

In this chapter all the necessary definitions of terms that are necessary to examine the operation of an electric power system are introduced, as well as the challenges that arise in the electricity production of island locations. Special emphasis is placed on the role of RES, since there are investigated their part in the coverage of electricity needs and the obstacles that impede their expansion.

2.1Electric Power System Overview

An Electric Power System (EPS) is the sum of the infrastructure and equipment (generators, transformers, transmition lines, switches, etc) that are used in order to provide electric power in a safe and uninterrupted way to specified geographical regions, that will be referred as loads [14]. Therefore, an EPS should be designed and constructed to meet the following demands:

- Cover the electric energy whenever needed (kWh)
- Cover the load demand of the needed amount of power (kW)
- Meet the power quality standards according to the EN 50160 [15]
  - Stable frequency (at the nominal value of 50 Hz)
  - Voltage range inside the predetermined limits based on the international standards I.E.C (International Electromechanical Commission)
- Accomplish all the above with the least economic and environmental cost

The sum of the infrastructure and equipment can be divided into three subsystems, accordingly [16]:

1. Power Generation System
2. Power Transmission System
3. Power Distribution System

Power Generation System includes all the stations of electric power generation, that utilize either conventional power sources like coal and diesel, or renewable energy sources, like photovoltaics (PV) and wind farms (WF), along with the transformers that step up the voltage level. At these high voltage level, the Transmission System is able to transfer electric energy over long distances with minimum power losses [16]. In Greece, the voltage levels at the Transmission System is 150kV for High Voltage (HV) level and 400kV for the Super High Voltage (SHV) level [8]. The Distribution system includes the rest of the network that provides electricity at the Medium Voltage level (15/20kV) and Low Voltage level (380V), to the end consumers [14]. In the following picture a schematic representation of an EPS is presented.

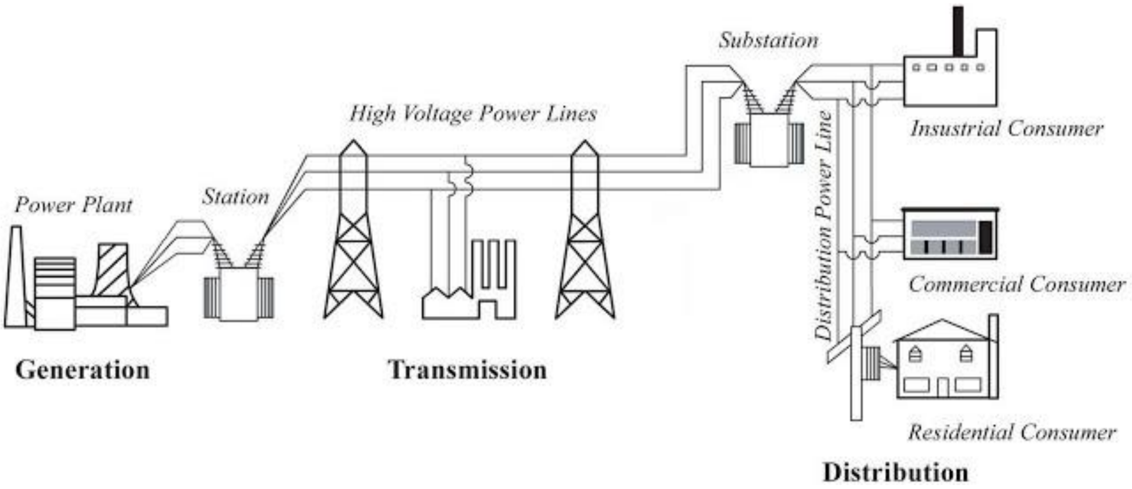


Figure 5: Electricity Production System [21]

As it has already been described, an EPS at its traditional form does not include any facility to store energy. As a result, the amount of electric power generation must be equal to the load demand every time, large differences between these two parameters can cause deviations in the frequency and voltage levels on the whole EPS [17].

2.2 Classification of Electric Power Systems

Even though, it is preferable for an EPS to have a large size, as it is more stable and robust [17], there are certain reasons that don't allow the expansion of electric networks in all the geographical regions that require electricity. The main reason is the morphology of isolated areas that increase the construction cost of Transmition Systems would connect them with the main Power Generation Systems, such regions are islands, with smaller or bigger sizes, and several remote and unapproachable mainland areas [5]. Energy generation, transmission and distribution has many differences in the case of small systems developed in remote regions than the systems established in larger geographical areas [14].

The main classification according to their operation, is the following:

- Autonomous/Isolated (Non-Interconnected) Electric Power Systems
- Interconnected Electric Power systems

More specifically, as Autonomous EPS (AEPS) systems are characterized the ones that are installed on islands or on isolated regions and do not have the capability of interconnection with a broader sum of other electrical systems [5].

2.3 Characteristics of EPS on Non-Interconnected Islands

The EPSs on Greek islands can be fully autonomous, although several islands have been interconnected, in each case the EPS have special characteristics that will be analyzed as follows. The range of energy consumption in NII can vary between 300MWh and 300.000MWh, while peak load demand ranges from 100kW to 100MWh. NIIs can be categorized into four groups based on their energy charachetistics (annual demand and peak demand) [18].

- The first group includes 8 tiny scale islands with population up to 200 people. The annual energy demand is up to 2 GWh and peak demand is less than 1MW.
- Group 2 comprises of 7 small sized islands, in this case the annual energy production is up to 15GWh and peak demand is up to 5MWh.
- The third group involves 13 medium scale islands, with energy demand up to 100GWh per year and peak load demand up to 35 MW.
- Lastly, Group 4 contains all the big scale islands of Aegean Archipelago (apart from Crete) with installed capacity over 40 MW and an energy production that exceeds 100 GWh annually.

Category (scale)	Peak Load Demand	Electricity Production	Islands
Very small	< 1MW	<2 GWh	Agathonis, Agios Efstratios, Anafi, Antikithira, Donousa, Erikouses, Meganisi, Othoni
Small	<5 MW	<15 GWh	Amorgos, Astipalea, Kithnos, Samothrace, Serifos, Simi, Skiros
Medium	<35 MW	<100 GWh	Andros, Ikaria, Ios, Karpathos, Milos, Patmos, Andros, Lemnos, Mikonos, Santorini, Siros, Sifnos, Samos
Big	>40 MW	>100 GWh	Chios, Kos-Kalimnos, Paros, Rhodes

Table 1: Aegean islands classification in terms of Peak Load Demand and annual Electricity Production [18]

The above two values can indicate the island's annual energy demand, although they are not sufficient to fully describe the characteristics of electricity production. One significant parameter in island's energy demand is the **seasonality** of the load. Electricity demand varies throughout the year, with intense peaks at summer periods, largely owed to the island's touristic character and the extensive need for air-conditioning, contrary to much lower values of electricity demand in winter. Actually, in most cases the summer peak load demand may be one order of magnitude higher than the minimum winter electricity consumption [9] The intense variations in load demand force the systems to install thermal units will high capacity, in order to cover the intense energy demand, while in the winter these units operate at lower levels than their nominal ratings, with lower efficiency factor and high operational cost [14]. **Load factor** is defined as the fraction of the average load demand to the installed power of electricity generation units [17]. In islands the value of load factor is usually small, as compared to the size of the system [9]. A low load factor has a demand for a big energy deposit that leads to a high investment cost [17].

In NIIs there are several characteristics regarding the Distribution System. The geographical morphology of Greek islands impose the need for an extensive grid infrastructure, even though the load demand is low at the numerous dispersed locations [6]. Also, as the voltage level in Greek islands is up to 15kV (relatively low) [4] and there is extensive grid infrastructure for small load demand, the system is burden by high transmission losses [9]. Furthermore, there is usually one power plant in the island which can has large distance from the point of load demand [6]. Hence, the reliability of the power system to provide electricity to the consumers is low since energy is produced centrally, especially isolated consumers on the island are more vulnerable to faults that occur to the Distribution System [4].

Power generation at NIIs is mainly based on Autonomous Power Generation Stations (APGS) that utilize fossil fuels, mainly oil (mazut or diesel) as an energy source. Despite its high cost, oil is preferred for the ease of transportation with ships and its proven reliability as a fuel source [23]. As a result, AGPS have a high cost of energy production, especially in smaller sizes like the units used in NIIs [24]. Furthermore, there some serious disadvantages that derive from using oil as a power source. Unpredicted variances at its price, alongside with long term danger of dry up and the local pollution emitted from the power plant operation, urge the utilities to shift to a different mixture of energy sources to meet the consumption demand [3]. All the above, suggest that installation and operation of AGPS is uneconomical relatively to the mainland EPS, even though their existence is necessary.

To illustrate the difference in the cost of electricity production between the mainland interconnected system and the NIIs, in Figure 6 is presented the Average Variable Cost (AVC) of the electrical energy production for several NIIs and with the red line is represented the **System Marginal Price** (SMP). SMP is the value derived from the electricity market clearing for the country of Greece [19], the average value for 2019 is 63,83€/MWh [25]. As presented in the graph the value of AVC in NII is much higher than SMP. The size of the island (or group of interconnected islands) affects the value of AVC. In the case of several tiny-size islands AVC is remarkably higher, reaching values up to 5 times the SMP value.

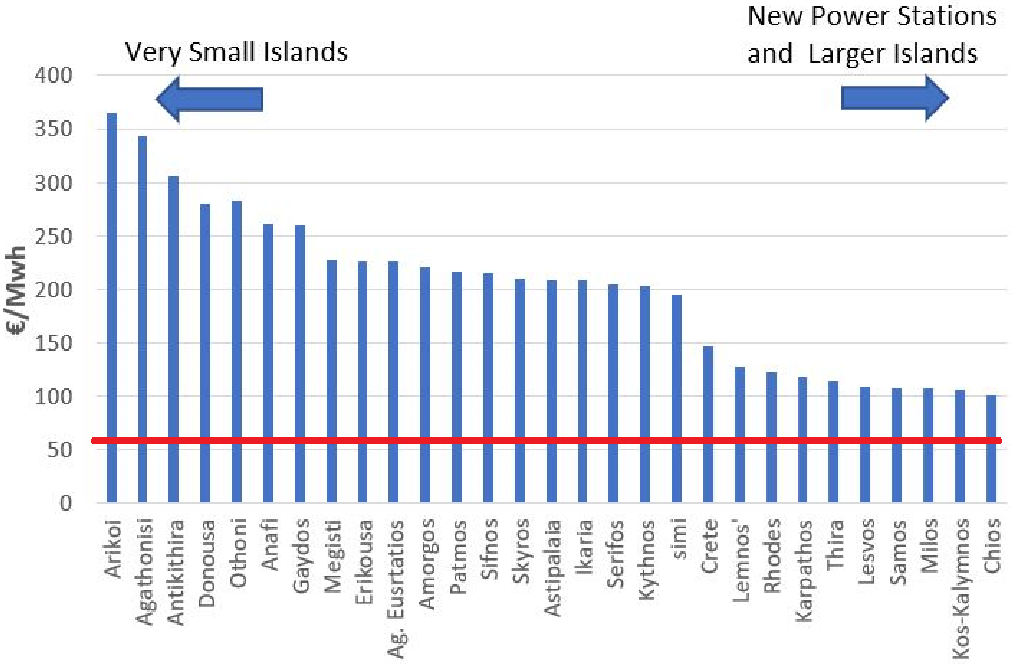


Figure 6:	Average variable generation cost of production per NII system, 2019 [24], [25]

The reduction of production cost can be achieved with better Management of energy production, with the increase of RES penetration levels and appropriate design of electrical grid infrastructures [20]. Greek islands have the advantage of high RES potential, the value of solar potential across the entire are is between 1350 and 1850kWh/m^2 annually and wind potential may even exceed annual average speed of 10 m/s for certain locations (see also Figure 7) [6].

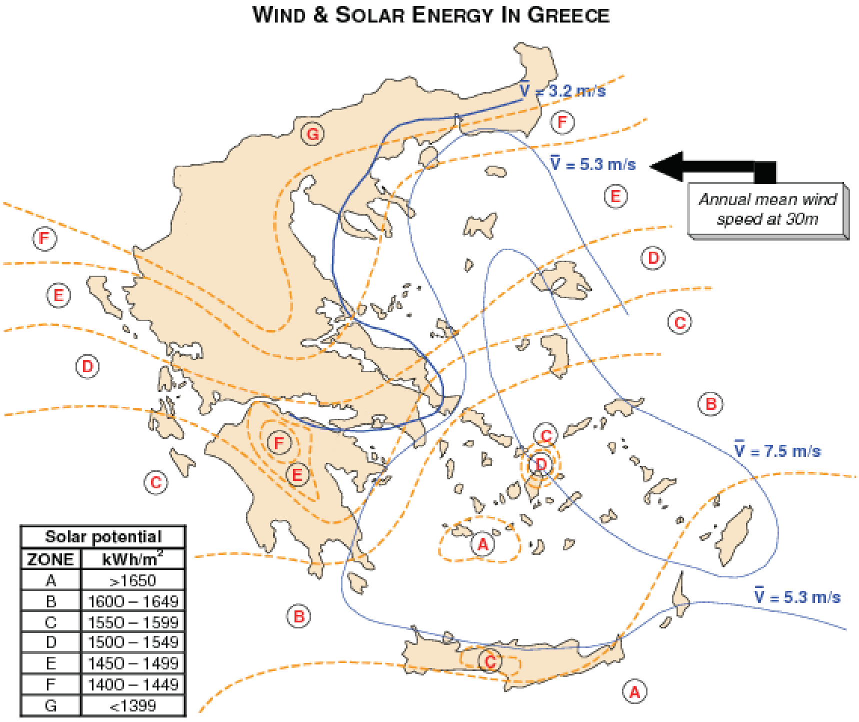


Figure 7: RES potential across the Greek territory [6]

Despite the vast RES potential of Greek islands, installation of new RES power stations is gradually discouraged after exceeding a certain capacity limit, owed to the fact that additional RES power implies severe curtailments that also entail significant financial losses for the RES power station owners. AEPS of NIIs are subject to additional constrains posed by the operation of thermal units and the character of a small isolated electrical system [20]. More specifically, the need to protect the operating machines from degradation and at the same time ensure the dynamic stability of the network requires the establishment of technical minima and dynamic penetration limits respectively [3], which pose restrictions in the absorption of energy from RES power stations.

In the diagram below the are shown the values of electrical energy production in the AEPSs for the years 2018-2020, with green color is represented the percentage of energy generated from RES and with orange the energy generated from conventional power sources. As shown in Figure 8 there are vast differences in the islands total load demand between winter and summer months, as has already been emphasized previously. Energy generation from RES is approximately steady from each month, with only small monthly deviations, the percentage in the monthly production is rather small.

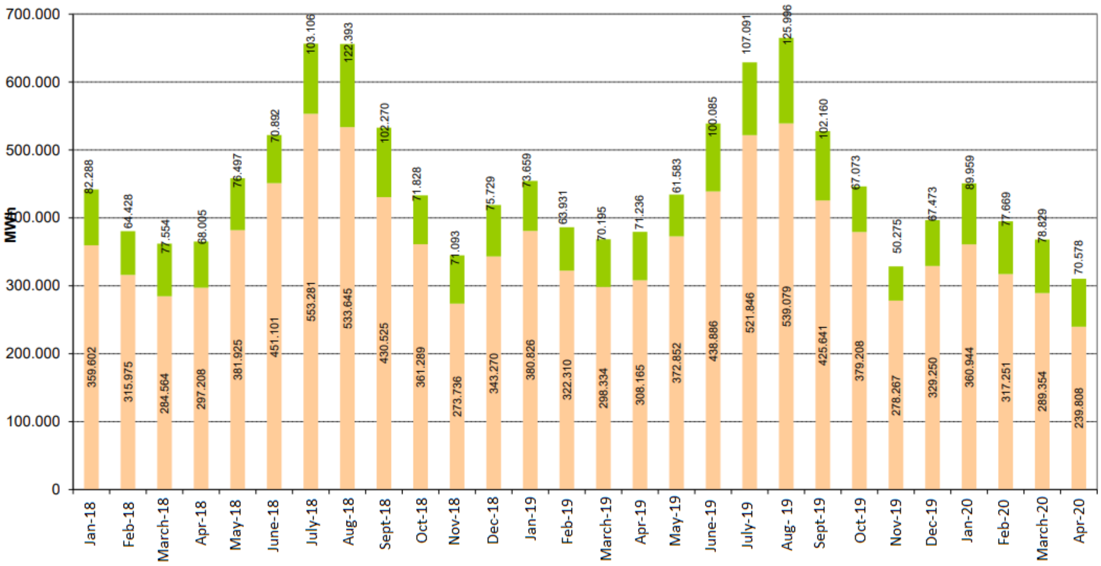


Figure 8: Electricity Production in NII for the years 2018-2020 [24]

There are two main directions that have been proposed to deal with the current situation. The first concerns the interconnection of the islands to the mainland grid, as already has been described, with special attention paid in order to avoid the possibility of overexploiting the local RES potential in order export energy to the mainland, at the expense of a more sustainable energy planning [23] The second approach suggests introduction of energy storage facilities that may support recovery of energy curtailments from RES power stations [9]. In the latter case it is important to select and design very carefully the mixture of RES and energy storage technologies, as there may be situations that may require extremely oversized systems in order to achieve increased penetration of RES in the local energy balance.

3 Energy Production and Storage

In the following chapter, a brief analysis of the different energy production methods in the Greek islands is conducted, with emphasis to RES. Also, there are presented the advantages and disadvantages of each energy production method based on the island's grid operation. Furthermore, the reasons why energy storage is vital in the near future in order to decarbonize the electricity production system will be analysed. Lastly, all the major different technologies along with the services that they can provide to the grid are presented.

3.1Energy Production

Energy production is mainly based conventional power stations. The main distinction of power stations can be made based on their way of operation [17].

- Base stations
- Peak stations

Base stations operate for longer time periods (24hours operations) in order to cover the basic demand of energy consumption. On the other hand, peak stations operate only at hours of high energy demand, peak hours, as their name suggests. Base stations can be characterized the stations that operate for a time period bigger than 70% of the year and peak stations are characterized the units that operate for a time period less than 30% of the year. [27]

Electrical energy production can be achieved with the utilization of several primary energy sources and has many variations from country to county, depending on the available resources, the energy policy and the geological and climatic characteristics [1]. Energy sources can be categorized to:

- Conventional, they are based on fossil solid, liquid or gas fuels, like oil, coal and natural gas. Energy production from nuclear power can also be included to conventional energy sources.
- Renewable energy sources (RES), they utilize inexhaustible power sources, like the sun, wind and water, to produce energy without consuming the restricted fossil fuel reserves [17].

The operator of electrical grid has to face two main problems. At the time periods when the load demand is low to incorporate as much energy production from RES in the energy mix, especially energy generated from WF. At time periods with high load demand (peak hours) it is important to be able to ensure a large amount of energy and power available to meet the demand, in a relatively short time period [16]. Energy management depends on the size of the electrical grid, in smaller electrical grids in locations like NIIs, the described problems are more intense [20].

3.2Renewable energy sources in NIIs

At NIIs the major part of energy production comes from the thermal power plants, which are considered to be the most reliable source of energy for electricity production [9]. Approximately 80% of energy demand is covered by thermal units and 20% by RES. More specific the percentage of energy demand covered by RES in NIIs is 12,6% from wind generation and 7,33% from PVs (Figure 9) [14].

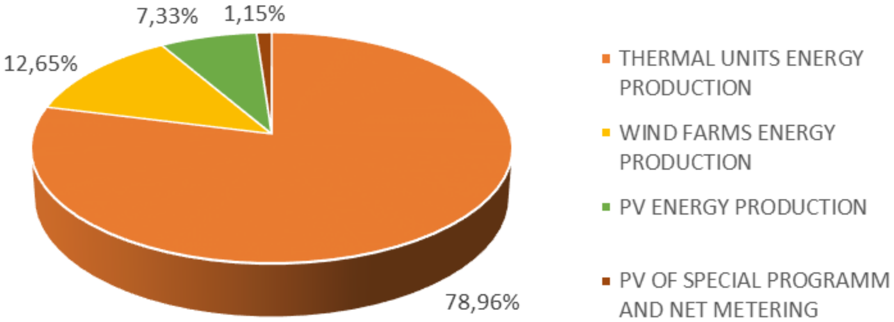


Figure 9: Energy Production at Greek NIIs [14]

The total installed capacity of RES in Greek islands is up to 440,75 MW. Wind generation has the highest amount of installed power, 306,75 MW, while photovoltaic generation comes second with 129.75 MW installed capacity. Also, it is important to be mentioned that in the island of Crete there is also energy generated from small hydro plants and Biofuel station [14]. The energy generated by the two major types of RES in NIIs is not stable throughout the year, the seasonal variance is presented in Figure 10. As presented on the graph, at the winter period energy production from wind and solar is significantly lower than the summer period. At this point it is important to be mentioned that, during the summer months along with the increased energy production from RES, there is also an increase in the island's load demand. The fact that is a synchronous increase in load demand and energy generation from can be an advantage that urges even more the need for utilization of the high-RES potential in Greek islands [5].

The installed capacity of RES on each island is proportional to the size of the island or the size of the grid of neighboror connected islands [14]. As Crete and Rhodes are the two largest Greek islands, they also have the biggest amount of installed RES installed, both form energy production from WFs and PVs, as presented in Figures 11 and 12. Nevertheless, several smaller islands, like Leros, have significant capacity of wind generation as compared to their sizes.

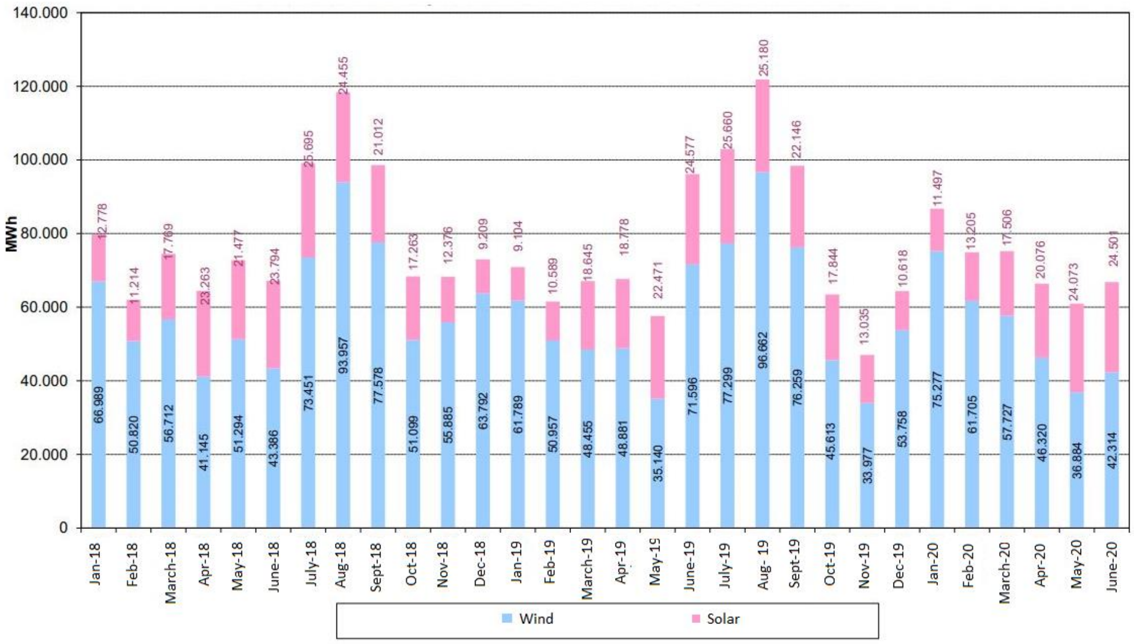


Figure 10: Monthly thermal and RES energy production in Greek NIIs (1/18-6/20) [24]

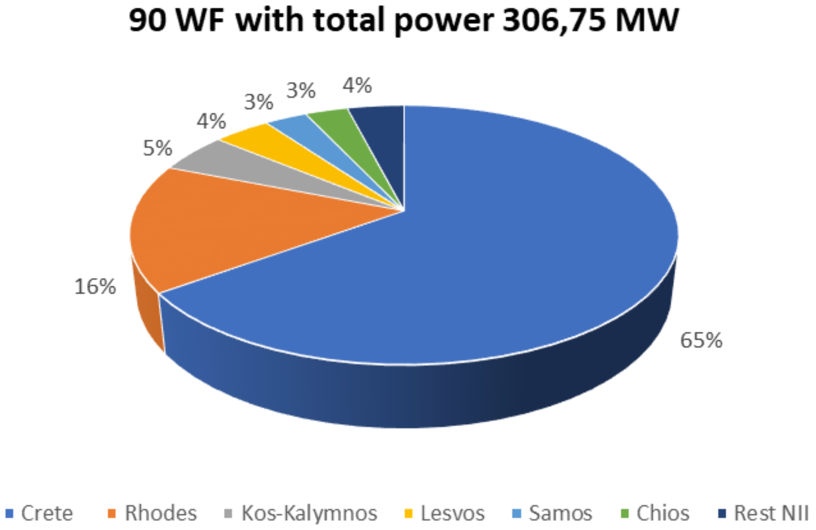


Figure 11: Wind production in Greek NIIs [24]

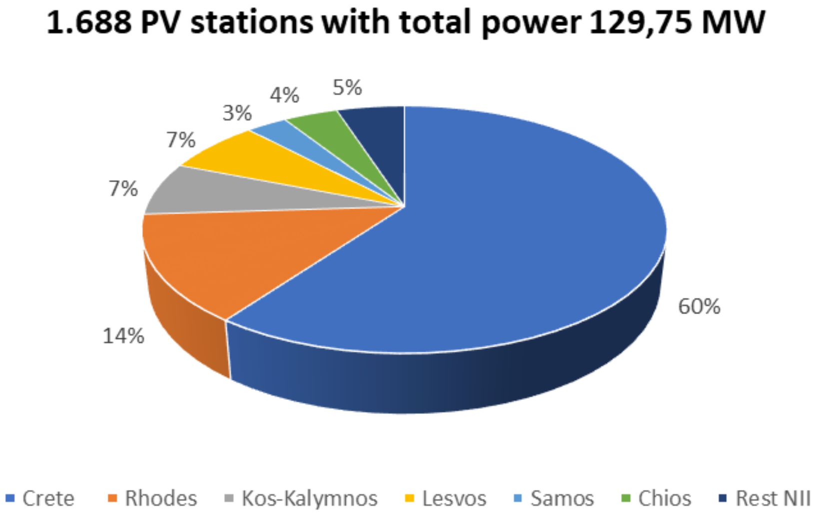


Figure 12: PV production in Greek NIIs [24]

NII	W/P Installed Capacity	PV Installed Capacity	Total Installed Capacity
Crete	200,29	78,29	279,88 [1]
Rhodes	48,55	18,16	66,71
Kos-Kalymnos	15,60	8,78	24,38
Lesvos	13,95	8,84	22,79
Samos	15,20	4,37	13,12
Chios	8,85	5,17	14,02
Karpathos	1,40	1,16	2,56
Kythnos	0,67	0,24	0,91
Lemnos	3,04	1,89	4,93
Milos	2,65	0,62	3,27
Patmos	1,20	0,15	1,35
Sifnos	1,20	0,20	1,40

Table 2:RES installed capacity in the major Greek NIIs [24]

Except from the installed capacity, it is also important to investigate the amount of energy produced per installed kW and the energy that is absorbed from the grid. Capacity Factor (CF) is defined by the factor of actual generated energy to the theoretical maximum energy that could be generated if the equipment was operating all time at the level of nominal power [26]. The following relation can calculate the value of CF:

$$CF = \frac{E}{8760 \times P_n} \quad [26] \qquad (1)$$

E: Actual Annual Generated Energy

P_n: Nominal Power

Capacity factor is strongly related to the economic viability for an investment in the energy sector. The value of CF is usually between 25% and 35%, although there is a

---

[1] *A small Hydro-plant (300kW) and one Biofuel station (990kW) are also included*

possibility to reach higher values when for instance the installation of a WF is at a region with high average value of wind speed [26]. In Figure 7, the values of annual average wind speed for Greece are depicted. As it is depicted, islands have high values of wind speed, which is an advantage that can attract investments to further utilize the wind potential [6].

Although, there are several cases that even if the wind potential is relatively high, CF is not as high as expected due to technical or operational issues that force WF to generate power only for specified time periods [11]. Even though the grid operator is obliged to absorb with top priority the energy generated from RES units, at the same it should be reassured the safe operation of the NII system. Technical restrictions of thermal units along with the necessity to maintain power reserve force the operator to constrain the energy absorption from RES units. The upper limit of RES absorption is expressed as a percentage of the instant load, in any case this percentage cannot be lower than 35% for bigger size islands and 30% for middle and small size islands [27].

Cuts of power generated from WFs show that there is no point on installing any further wind generators, because the island will not be able to absorb the generated power [a3]. Energy generated from RES should be more reliable in their power supply to the grid even if there are variances in the weather profile. Energy storage can solve the issues related with the power supply instability as energy is stored when there is an excess of power generation and feuded to the grid when the load demand increases [6]. The need for energy storage at Greek islands is based on three factors. Traditional the technical minima of large thermal units and the peaks of load demand were the main factors, but now there is one more reason that comes from the need to increase the percentage of generation from wind in the electrical production system [6]. A proven method of implemented storage units to NII are HPS, that consist of a RES station and an energy storage facility and can be used as tools in order to expand the capacity of RES stations in Greek islands [27], as it will be analyzed in the following chapters.

3.3Energy storage

At an electrical grid, interconnected or isolated, the load demand must be equal to the energy generation, this means that the absorbed energy from the consumers, the load demand, must be equal, small deviations are acceptable, with the energy generated from the various energy sources, conventional thermal power plants or RES [14], [17]. The extra amount of energy that might generated is useless and so is rejected, like in the case of WF in NII that was previously mentioned. Energy storage facilities can provide a solution to the energy management problem in the electrical grids. Energy is stored during times when electricity is plentiful and inexpensive (time periods with high-RES production) or when the demand is low, and later returned to the grid when demand is high and electricity prices tend to be higher [28]. Furthermore, they are able to provide ancillary services to the grid and make its operation more reliable [29], a further analysis on the topic on of energy and ancillary services will be given in the relative chapter below.

Utility scale energy storage can have different forms (Figure 13) that can be implemented in Greek islands and electrical grids in general, at different levels. Central storage units installed in the system operation level can provide several services to the grid, that will be analyzed in the following chapter. At the level of distributed energy generation, the combination of storage with RES units can either form HPS or behind the meter generation schemes. Network level storage can assist the operation of the electrical grid, although their implementation is not expected in the near future, at least for Greek islands. Finally, consumers can have storage units, either as electric vehicles or as stationary behind the meter units, combined with efficient load management techniques [28]. From a technical point of view all typologies can be implemented, but the regulatory framework and the economic feasibility are two severe constrains that stop the installation of specific kinds. At the moment, Central Storage units and HPS have the most interest for installation in Greek Islands [30].

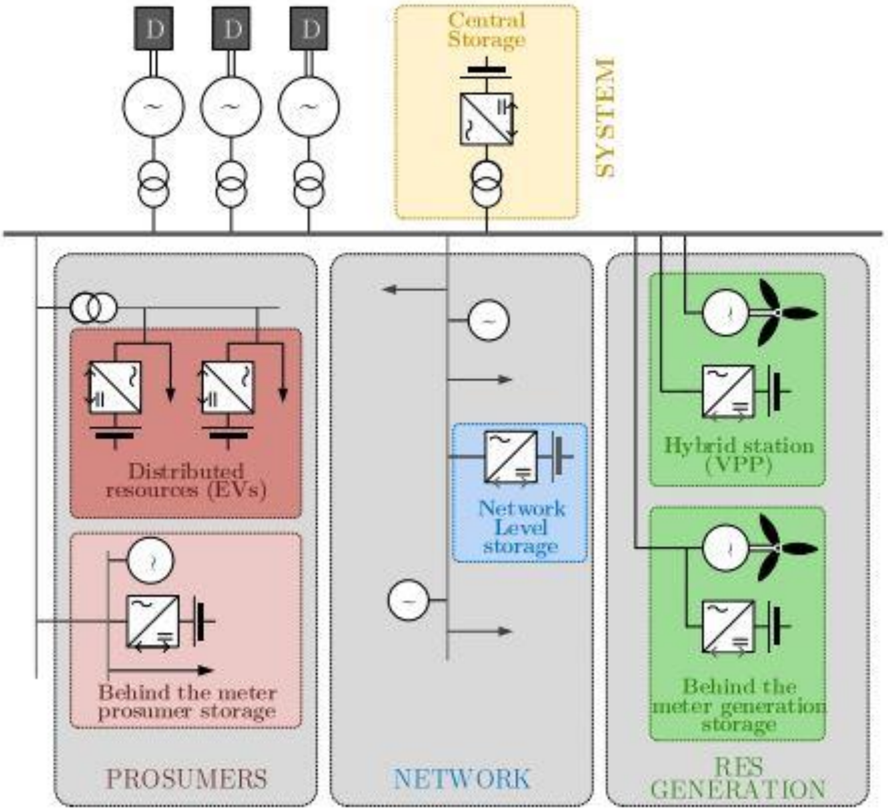


Figure 13: Typologies of energy storage [28]

3.4Energy Storage technologies

Electrical energy is not able to be stored efficiently in its form (electricity) for utility scale applications, so it has to be transformed in other physical forms that are easier to be stored [f20]. In general energy storage systems can be categorized as mechanical, electrochemical, chemical, electrical, or thermal devices, depending on the storage technology used (Figure 14) [32]. Mechanical Systems, including pumped hydropower generation, consist the oldest and most mature technology for utility scale energy storage [31]. However, the morphology of the island locations is not always suitable for the development of a PHS system. On the other hand, in the current market exist a variety of promising technologies like flywheels, batteries or Hydrogen storage that could be implemented in Greek NIIs [9].

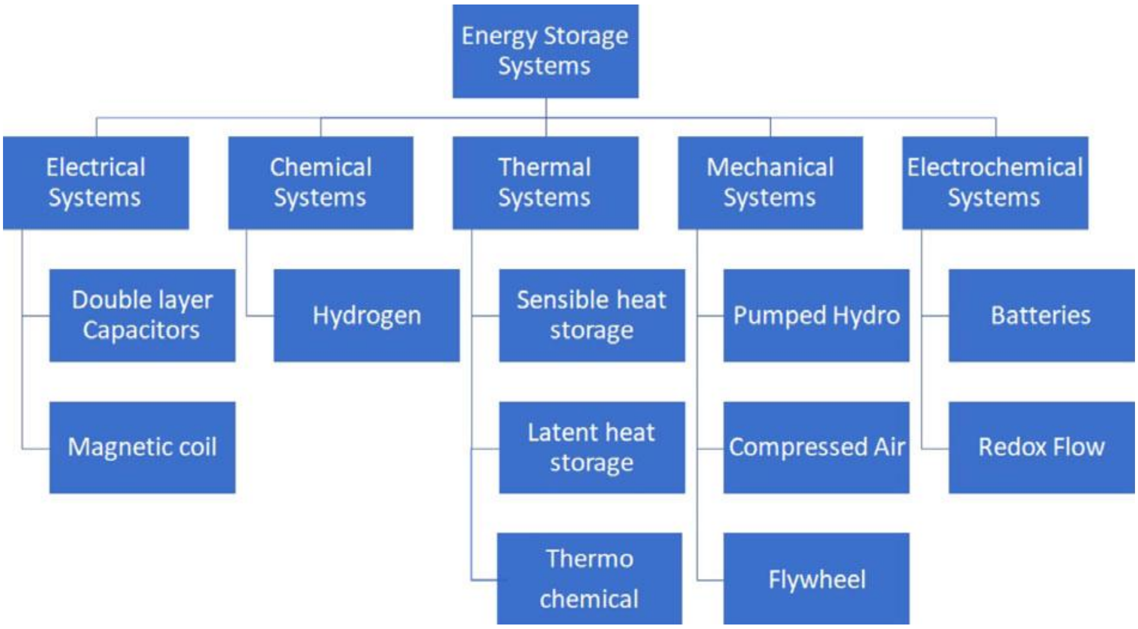


Figure 14: Types of Energy storage Systems [32]

In the following chapters the different types of commercially available energy storage technologies are analyzed. It is important to have a clear view about the advantages and disadvantages that each technology has, as there is not only one type of storage that can tackle all the different needs that an electric grid might have. Special emphasis will be given to batteries and hydro pumped storage along with the proper criteria in odred to categorize each technology for its intended application.

3.4.1 Batteries

Batteries are in general the most popular type of energy storage for smaller scale applications and they are included in the devices that store energy in the electrochemical from [29]. A battery system is comprised of cells connected in series or parallel to achieve the desirable electrical characteristics. A battery is charged when a potential difference is applied to its poles that enables a chemical reaction inside the battery. The reverse chemical reaction discharges the battery [33]. Today, most common battery chemistries are based on lead, nickel, sodium and lithium, there are also emerging technologies like flow batteries utilize various transition metals like vanadium, chromium, and iron as the electroactive element (Figure 15). Each storage type has distinct characteristics, namely, capacity, energy and power output, charging/discharging rates, efficiency, life cycle, cost and safety that need to be taken into consideration for possible applications [31].

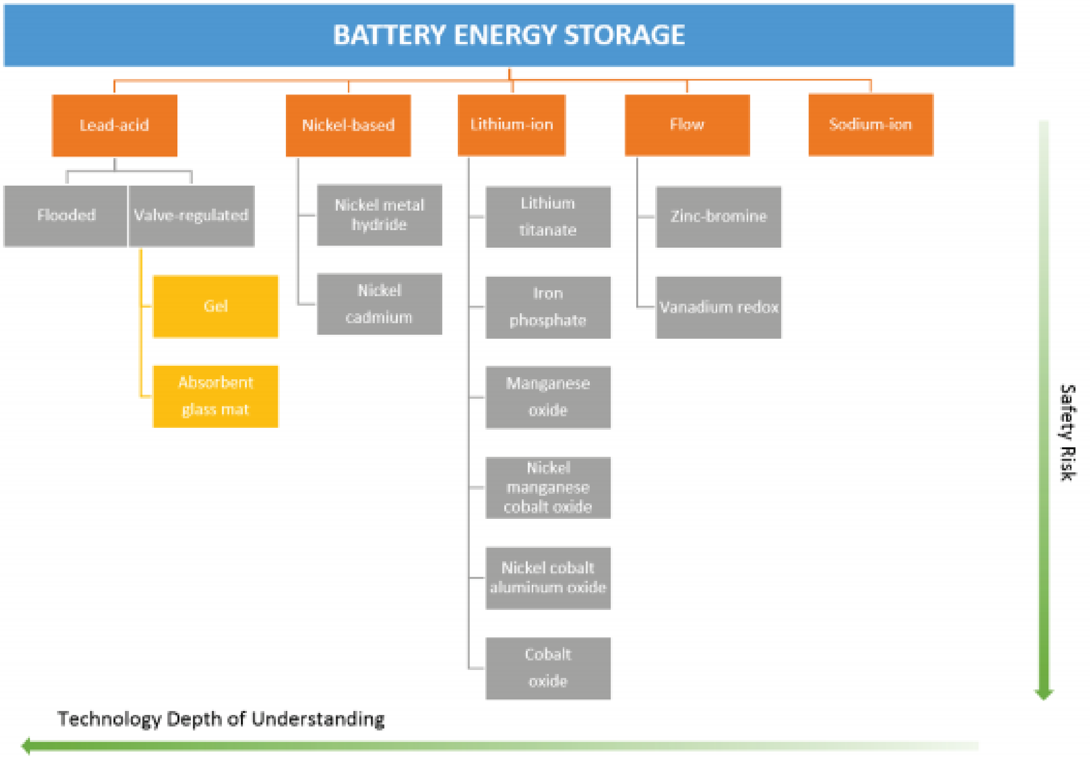


Figure 15: Types of rechargeable battery technologies [31]

Not all batteries are created equal, even batteries of the same chemistry. The main trade-off in battery development is between power and energy: batteries can be either high-power or high-energy, but not both. Often manufacturers will classify batteries using these categories. Other common classifications are High Durability, meaning that the chemistry has been modified to provide higher battery life at the expense of power and energy [33].

In the following chapters the different types of batteries are analyzed, but firstly the definitions of several key terms, for utility scale storage, are given, that will help the reader to have a deeper understanding and be able to compare the different technologies.

Capacity or Nominal Capacity (Ah for a specific C-rate) : The total Amp-hours available when the battery is discharged at a certain discharge current (specified as a C-rate) from 100 percent state-of-charge to the cut-off voltage. Capacity is calculated by multiplying the discharge current (in Amps) by the discharge time (in hours) and decreases Cycle Life (number for a specific DOD) [31], [34].

State of Charge (SOC) (%) : is defined by the percentage of the present battery capacity to the maximum capacity. [33].

Depth of Discharge (DOD) (%): The percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity. A discharge to at least 80 % DOD is referred to as a deep discharge [34].

C- and E- rates: In describing batteries, discharge current is often expressed as a C-rate in order to normalize against battery capacity, which is often very different between batteries. A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. For a battery with a capacity of 100 Amp-hrs, this equates to a discharge current of 100 Amps. A 5C rate for this battery would be 500 Amps, and a C/2 rate would be 50 Amps. Similarly, an E-rate describes the discharge power. A 1E rate is the discharge power to discharge the entire battery in 1 hour [33],[34].

Round-trip efficiency: is expressed as a percentage and is defined by the fraction of energy discharged from a fully charged battery to the energy that is required to charge it again. In large battery systems round-trip efficiency can represent DC-DC or AC-AC efficiency of the system, in the second case the rest of electric losses (inverters) are also included [29],[34].

Life Cycles: The number of discharge-charge cycles the battery can experience before it fails to meet specific performance criteria. Cycle life is estimated for specific charge and discharge conditions. The actual operating life of the battery is affected by the rate and depth of cycles and by other conditions such as temperature and humidity. The higher the DOD, the lower the cycle life.with increasing C-rate [34].

Lead-Acid Batteries

Lead-acid batteries are the oldest form of rechargeable battery technology. It is common to see lead-acid batteries in a range of applications, including automotive, marine, telecommunications, and uninterruptible power supply (UPS) systems [35]. All lead-acid designs share the same basic chemistry. The positive electrode is composed of lead-dioxide, PbO2, while the negative electrode is composed of metallic lead, Pb. The active material in both electrodes is highly porous to maximize surface area [29]. However, not all lead-acid batteries are appropriate for use in electricity supply systems. Batteries in electrical systems must be deep-cycle batteries, meaning that they must be able to discharge a large amount of energy in one cycle, which is made possible because they have a high useful energy capacity relative to their actual energy capacity [33].

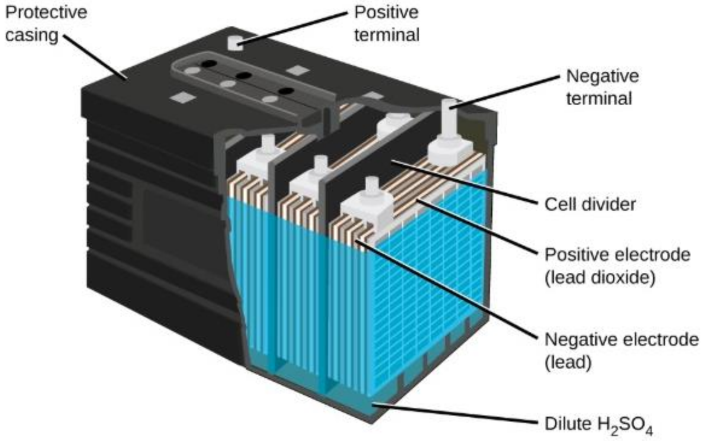


Figure 16: Lead Acid Battery Diagram [53]

Deep-cycle lead-acid batteries can be split into two common classes: wet cell and valve regulated (VRLA) batteries. A wet cell uses distilled water as part of its electrolyte, that has to be replaced on a regular schedule (typically about twice a year). VRLA batteries require less maintenance and are less sensitive to non-upright orientations than wet cells. The primary distinctions between these types of batteries are the initial capital cost (wet cells are less expensive) and maintenance (VRLA batteries require less maintenance and will not spill). VRLAs can be either of the absorbed glass mat type or the gel type. [36]

Lead-acid batteries are the most commercially mature rechargeable battery technology in the world. The main advantage of Lead-Acid batteries is their low cost per Watt-hour. The relatively manufacture process makes the capable to be produced on local basis. Furthermore, they have good performance in low or high temperatures and there is no need to maintain strict environment conditions [35].

On the other hand, there are several challenges that have to be taken into consideration about the selection of a Lead-Acid battery system. Concisely conveying the capacity of a lead-acid battery system is complicated and challenging. A lead-acid battery should never be discharged below 20% of the stated capacity (i.e. an 80% DoD) and under normal operation should never fall below a 50% DoD. Another challenge is that the capacity of a lead-acid battery decreases if power is pulled out quickly. Manufacturers will report capacities based on the time that it took to deplete the battery, with the notation C/Time (so C/20 is the current draw at which the battery will last for 20 hours). Regardless, the useful storage capacity is much less than the nominal storage capacity reported by manufacturers [36]. The lifetime of a lead-acid battery depends on a number of factors. The positive plate inside a lead-acid battery is corroded each time the battery is cycled, and its thickness directly relates to battery life [37]. The lifetime of a lead-acid battery also depends on how the battery is charged and discharged. Most manufacturers recommend that their lead-acid batteries not be discharged below about 30% to 50% of the specified battery capacity. Since a lead-acid storage system’s life is susceptible to overcharging and high ambient temperatures it requires a charge controller to properly manage the battery’s state of charge and the environment in which the battery is placed. It is also important to employ a skilled technician who understands how to fill wet cell batteries, how to equalize the charge, how to clean the contact posts and how to perform other routine maintenance tasks [38].

Nickel Based Batteries

Two main types of nicked based batteries, nickel- cadmium (NiCd) and nickel- metal hydride (NiMH) existi in the market. The nickel–cadmium battery (NiCd) uses nickel oxide hydroxide and metallic cadmium as electrodes [31]. Compared with other types of rechargeable batteries, NiCd batteries offer satisfactory life-cycle characteristics and improved performance at low temperatures with a good capacity retention at high rates. However, the material costs are higher than that of the lead acid batteries. Moreover, NiCd cells experience the so called “memory effect” and high self-discharge rates which have a great impact to their performance characteristics. In addition, environmental concerns on the disposal of the toxic metal cadmium has dramatically reduced the use of NiCd batteries. As a result, NiCd rapidly lost market share to nickel-metal-hydride (NiMH) and Li-ion batteries in the 1990s [29]. A NiMH battery can have two to three times the capacity of an equivalent size NiCd. Main applications of the NiMH batteries are found in consumer electronics and hybrid vehicles due to the technology maturity and their competitive cost to Li-ion batteries [39].

Typical characteristic of nickel-based batteries is high energy density which can be translated into either long run times or reduction in the space needed for the battery. Economical pricing is one of the greatest advantages, especially NiCd batteries offer the lowest cost per cycle. As nickel-based batteries exist in the market for quite a long period of time, they are available in a wide range of sizes and performance options [33]. They can be characterized rugged for two reasons, they present high number of life cycles with proper maintenance and there is the availability of ultra-fast charging causing little stress to the battery. [31]

At the disadvantages of nickel based batteries is listed the high self-discharge rate that they present. More specific Ni–MH has about 50% higher self-discharge compared with the Ni–Cd [29]. New chemical additives improve the self-discharge, but at the expense of lower energy density. Furthermore, memory effect can affect the operation of batteries in utility scale energy storage systems, as there is the need for periodic discharge [33].

Lithium-ion (Li-ion) Batteries

A battery technology that has been steadily improving over the last decade is the lithium ion battery (Li-ion) [39]. In this type of rechargeable battery lithium ions move from the negative electrode to the positive electrode during discharge, the process is reversed during charging. With a high energy density, negligible memory effect and low self-discharge, Li-ion batteries are one of the most popular types of rechargeable batteries for portable electronics [29]. In recent years, they are also growing in popularity for military, Plug-in electric vehicle (PEV), and aerospace applications. For small mobile applications, Li-ion may be considered a mature technology; however, in electrical grid applications, Li-ion is still developing. Li-ion batteries are more commercially proven in applications in which size and weight need to be minimized [31].

Li-ion batteries have a number of different chemistries. Common examples include lithium-cobalt oxide (LiCoO2), lithium-nickel oxide (LiNiO2) and lithium iron phosphate (LiFePO4). Although there are some performance and lifetime differences among these technologies, at a high level they provide excellent weight-to-energy and weight-to-power ratios and slow self-discharge loss when not in use. on batteries [33]. If overcharged or overheated, Li-ion batteries can rupture and, in some cases, explode. Both protective circuitry and fail-safe mechanical protections are typically included with a modern Li-ion system and have minimized these safety risks. Regardless, the ambient temperature where the battery will be used should be considered when using Li-ion storage in an application. Exposure to high temperatures can also shorten a Li-ion battery's expected lifetime. Compared to lead-acid batteries, Li-ion batteries have more consistent charging and discharging characteristics and can handle deeper discharges from their stated capacities with less impact on lifetime. Li-ion batteries tend to cost more upfront but have longer lifetimes [31].

Different types of Li-ion battery chemistries present different performance, cost and safety features that can suit a variety of applications. For example, lithium cobalt oxide (LiCoO2) batteries are used in most handheld electronics due to their high energy density and low weight. Other types such as Lithium iron phosphate (LiFePO4), lithium-ion manganese oxide batteries (LiMn2O4, Li2MnO3, or LMO) and lithium nickel manganese cobalt oxide (LiNiMnCoO2 or NMC) offer lower energy density, but can provide longer lifetime and inherent safety. LFP is the preferable battery type for energy storage applications as it combines a high number of high cycles (2000and higher) with acceptable charge/discharge rates (around 1C). [33]

The characteristics of Li-Ion batteries that have established them in the battery market are the highest energy density and high load capabilities, alonght with the safety and low maintenance needs. Their charge algorithm is relatively easy and the charge time periods are relatively short [40]. The technology is still under development, therefore further performance improvements may be expected in the future [29].

On the other hand, there is a need for protection circuit to prevent thermal runaway if the batteries are stressed. Also, they are susceptible to environment factors, as degradation increases in high temperature conditions and there are difficulties when trying to rapid charge the batteries in freezing temperatures, so an HVAC system in the battery storage area is necessary to maintain the optimum operation conditions [41].

Figure 17: Containerized lithium-ion energy storage system [42]

Sodium Sulfur Batteries

A sodium–sulfur (NaS) battery is a molten-salt battery constructed from liquid sodium (Na) and sulfur (S) and their operation is based on reaction between a sodium electrode and a sulfur electrode. NaS batteries are fabricated from inexpensive materials, which forms one of the main advantages of this technology type. NaS batteries have high energy density, high efficiency of charging/discharging (89–92%) and long cycle life. The operation of this type of batteries is flexible enough, since cells are functional over a wide range of conditions (rate, depth of discharge, temperature) [29].

The main drawbacks of the NaS battery are the operating temperatures of 300oC to 350oC and the highly corrosive nature of the sodium polysulfides. Battery cells become more economical with increasing size, therefore NaS batteries are considered more suitable for stationary energy storage applications [43]. Typical applications of NaS batteries are distribution network support and grid services and renewable energy integration. The technology has a great potential for grid services since it has a long discharge time and can respond precisely to improve power quality issues in the grid [31],[33].

Flow Batteries

A Flow battery cell is a type of electrochemical cell where chemical energy is provided by two chemical components (electrolytes, positive and negative) within the system with ion selective membrane that separates them. Electric current occurs from the ion exchange through the membrane while both liquids while both liquids circulate in their own tank (Figure 18). A flow battery is consisting of multiple electrochemical cells connected in series in a stack. These stacks are then connected in series and/or stacks to form a Flow Battery Energy Storage System (FBESS) [44], 22.

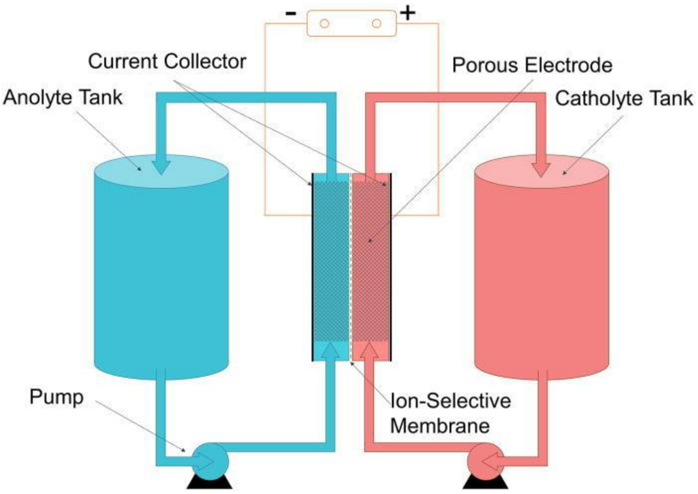


Figure 18: Flow battery diagram 22

Two prominent flow battery chemistries are commercially viable: **vanadium redox** batteries (VRB) and **zinc bromide** batteries (ZBB). The VRB technology has more expensive cell stacks but less-expensive electrolyte than the ZBB. Additionally, the VRB electrolyte will, according to many estimates, last longer than 100 years. In general, ZBB is being marketed toward small-to-midsize systems, whereas VRB is being marketed to larger utility customers. Currently, the most cost-effective flow battery that exhibits good performance and safety is the all vanadium redox flow battery 22.

Flow batteries are considered unique in that the power and energy of the battery are entirely decoupled. The energy capacity is a function of the electrolyte volume (amount of liquid electrolyte), and the power is a function of the surface area of the electrodes. Flow batteries have several technical advantages over conventional rechargeable batteries, but a monitoring and control mechanisms is required 22. Flow batteries are inherently safe as the aqueous electrolyte is non-flammable. They have demonstrated long cycle life and the cycle life is not dependent on the depth of discharge. Furthermore, most flow batteries can be fully discharged (to 100% DoD) without damaging the equipment, which expands the operational range of their storage capacity [44].

One of the biggest challenges for flow batteries is their low energy density. The cell stack is roughly the size of a similarly sized traditional battery, but the electrolyte requires tanks, piping and pumps to hold and transport the fluid. Although flow batteries tend to have low lifetime costs of storage compared to other technologies, they also have high capital costs, which can become cost-effective due to the long-expected lifetime and low operational costs [44].

3.4.2 Pumped Hydroelectric Storage

The most common type of energy storage facilities for utility scale storage applications is pumped hydroelectric storage (PHES), since it accounts for 97% of energy storage worldwide [45]. The operation of an PHES is based on two reservoirs, one at a higher elevation and one at a lower level. Energy is stored in the form of water in the form of water in the upper reservoir, pumped from the reservoir at lower elevation. During periods of high electricity demand, power is generated by releasing the stored water through turbines in the same manner. During periods of low demand (usually nights or weekends when electricity is also lower cost), the upper reservoir is recharged by using lower-cost electricity from the grid to pump the water back to the upper reservoir [46].

Pumped hydro plants as a technology has long life cycle, a typical lifetime periods for is estimated at 50 up to 60 years. The efficiency in the operation of this type of stations is about 76% to 85%, depending on design. PHES are characterized as relatively low energy density systems that require either large flows and/or large differences in height between reservoirs [47]. Pumped storage hydropower can provide energy-balancing, stability, storage capacity, and ancillary grid services such as network frequency control and reserves. This is due to the ability of pumped storage plants, like other hydroelectric plants, to respond to potentially large electrical load changes within seconds. Pumped storage historically has been used to balance load on a system, enabling large thermal plants to operate closer to their higher efficiency rates. Pumped storage projects also provide ancillary benefits such as firming capacity and reserves (both incremental and decremental), reactive power, black start capability, and spinning reserve. In the generating mode, the turbine-generators can respond very quickly to frequency deviations just as conventional hydro generators can, thus adding to the overall balancing and stability of the grid. In both turbine and pump modes, generator-motor excitation can be varied to contribute to reactive power load and stabilize voltage. When neither generating nor pumping, the machines can be also be operated in synchronous condenser mode, or can be operated to provide spinning reserve, providing the ability to quickly pick up load or balance excess generation [48].

Restrictions related with the development of PHES is the selection of a morphologic area that provides the required elevation difference with acceptable elevation angles that facilitate the water pipe installation, in combination with an available source of water. In addition, several highly trained consultants and engineers will be necessary to analyze, design and build the storage system. Furthermore, the licensing process will likely be lengthy and involve a consultation process with residents and other affected stakeholders [47].

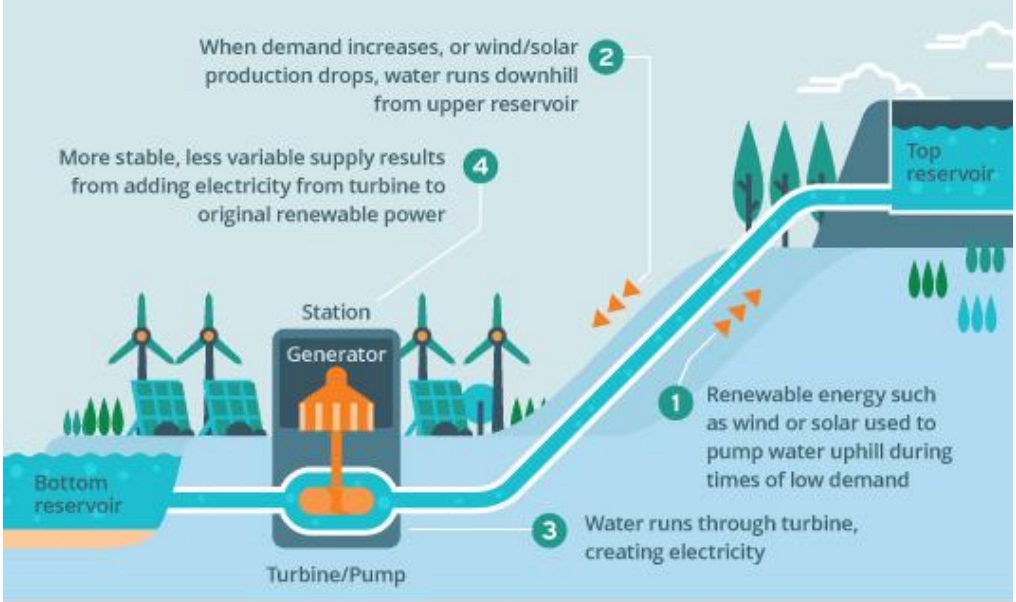


Figure 19: Pumped Hydroelectric Storage [45]

3.4.3 Flywheels

Flywheels use a large, heavy, rotating wheel to store energy. Electricity is converted into kinetic energy for storage, increasing the speed of the rotating wheel. The wheel slows when energy is discharged from it. There are two types of flywheels: high-power flywheels and long-duration flywheels. Long-duration flywheels are still in early research and development and are not commercially viable. High-power flywheels store and release large amounts of power for very short periods of time—typically, about one minute. They are often used as part of an uninterrupted power supply to bridge between sudden power outages and starting a generator. They are also well-suited for reducing ramp rates from intermittent renewable technologies, such as solar and wind, improving system stability [29].

Some of the key advantages of flywheel energy storage are low maintenance, long life (some flywheels are capable of well over 100,000 full depth of discharge cycles and the newest configurations are capable of even more than that, greater than 175,000 full depth of discharge cycles), and negligible environmental impact. Flywheels can bridge the gap between short-term ride-through power and long-term energy storage with excellent cyclic and load following characteristics [44]. However, they do not currently provide cost-competitive long-term storage. In some applications, they may be useful to improve short-term power stability (less than one minute) and improve delivered power quality (e.g. reduced reactive power).

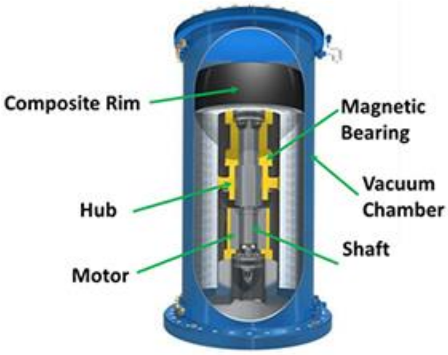


Figure 20: Flywheel Diagram [29]

3.4.4 Large-Scale Compressed Air Energy Storage (CAES)

In this type of technology energy is stored by compressing ambient air or another gas is and storing it under pressure in an underground cavern or container. When electricity is required, the pressurized air is heated and expanded in an expansion turbine driving a generator for power production [50]. The special thing about compressed air storage is that the air heats up strongly when being compressed from atmospheric pressure to a storage pressure of approx. 1,015 psia (70 bar) [29]. The heat of compression therefore is extracted during the compression process or removed by an intermediate cooler. The loss of this heat energy then has be compensated for during the expansion turbine power generation phase by heating the high pressure air in combustors using natural gas fuel, or alternatively using the heat of a combustion gas turbine exhaust in a recuperator to heat the incoming air before the expansion cycle. Alternatively, the heat of compression can be thermally stored before entering the cavern and used for adiabatic expansion extracting heat from the thermal storage system [50].

Conventional large-scale CAES differs from many other storage technologies in that the stored energy is not converted directly to electricity but rather used to improve the efficiency of fossil fuel–based electrical production. A typical value that characterizes the roundtrip efficiency of these systems is around 70%, this assumption is based only on the efficiency of compression and expansion, the type of fuel is not taken into consideration [49]. CAES technology requires extensive geologic surveys, and costs will be site-specific. Regarding the capacity, existing CAES systems have nominal power over 100 MW and consist the only available solution for PHS systems [47].

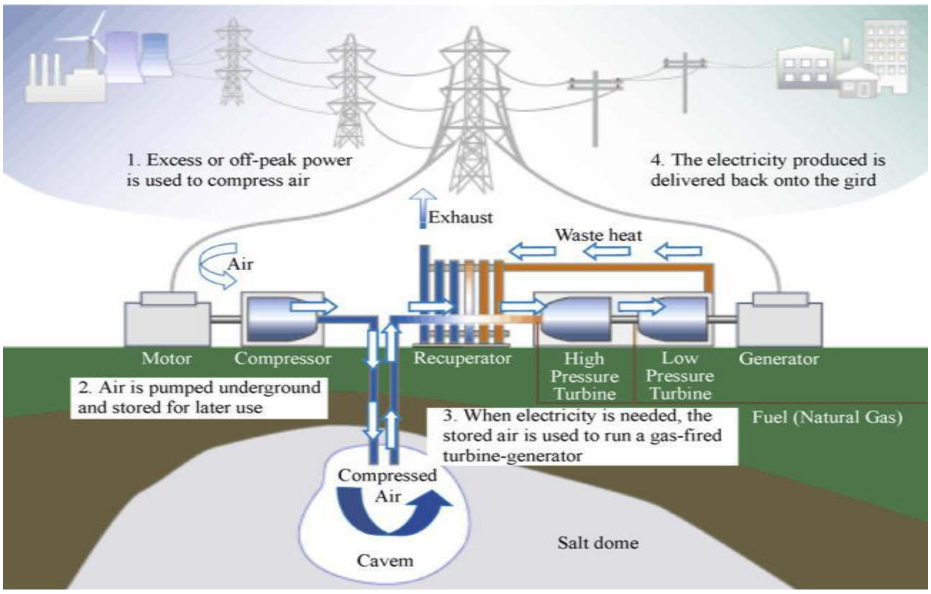


Figure 21: CAES schematic diagram [50]

3.4.5 Hydrogen Storage

In this type of storage, electrolysis is the mechanism that converts electricity to hydrogen, which can be stored and eventually re-electrified. A hydrogen storage system consists of three major pieces of equipment: an electrolyzer, which uses electricity to remove hydrogen from water; a storage tank, which captures and stores the hydrogen; and a fuel cell (or generator), which uses hydrogen to generate electricity [51].

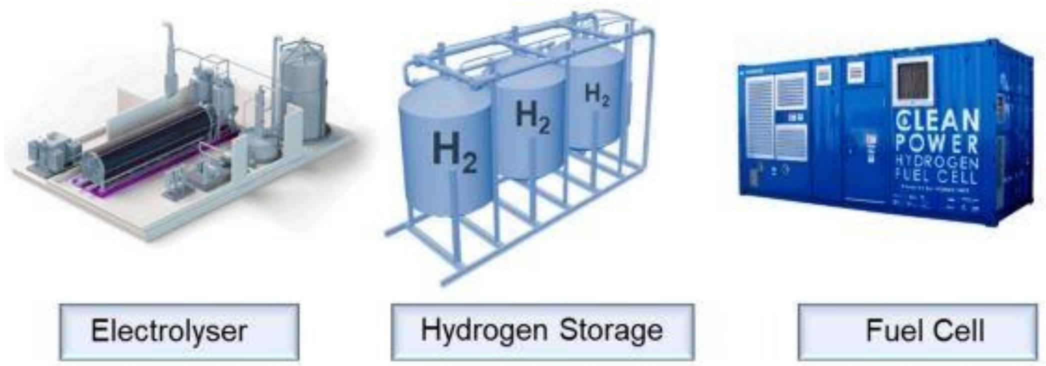


Figure 22: Hydrogen Storage system Components [51]

Hydrogen storage for grid applications is expensive, due largely to the roundtrip efficiency of storage [44]. Typical roundtrip efficiency values in pilot projects are in the range of 20% to 30% [29]. There are several restrictions for hydrogen storage to overcome this fundamental hurdle, and some argue that it cannot be done. Despite its efficiency challenges, strong interest exists in hydrogen storage for off -grid applications [44]. Lastly, several pilot projects worldwide have been developed including in Ramea, Newfoundland, Canada and Utsira, Norway; however, the reported efficiencies have been very low [29].

3.5 Applications of energy storage

The benefits of small-scale energy storage can be very useful in NII autonomous electrical systems, that are characterized from extended need of energy both for energy and ancillary services. In a NII system an energy storage unit can be incorporated in various ways, offering different type of services each time. The main services that can be offered in island grids are the following:

Energy Arbitrage: In markets where there is a significant difference in locational marginal price (LMP) of electricity at different times, energy arbitrage can be used to offset costs. Wholesale electricity is purchased and stored when the LMP is low to be resold when the LMP is high [35]. Larger scale utility storage systems are well suited to serve as capacity reserves as they can discharge during peak hours, displacing peak-thermal units and relieving the system operator from further investment in such type of units [37].

Flexible Ramping: At specific hours during the day Res penetration (especially from PV units) penetration, starts to increase, the shape of the load curve changes dramatically into the so-called solar duck curve. The duck curve is characterized by very high ramping requirements and was first prominent in the Californian power system (Figure 23) [55]. The system is required to ramp downwards in the morning when solar generation increases and ramp upwards in the evening when solar generation decreases and demand increases. Energy storage units would help flatten the duck curve by absorbing the energy generated from PV stations in the morning hours and injecting it back to the grid later in the evening hours when peak demand generally occurs [38].

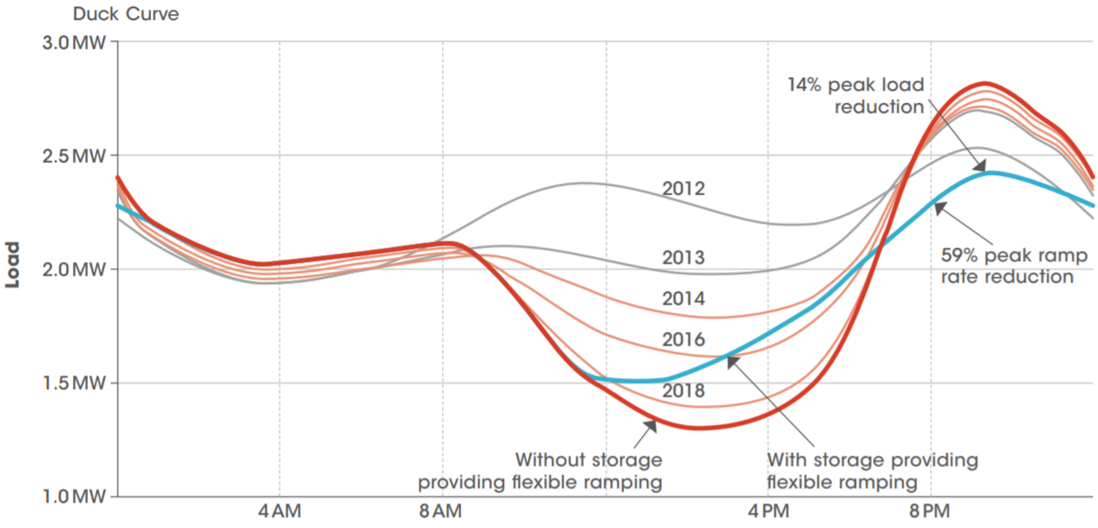


Figure 23: Impact on the duck curve of energy storage providing flexible ramping [55]

Frequency Regulation: An imbalance between the power supply and the power demand can lead to a dip or a rise in grid frequency beyond the specified limits. Frequency regulation involves regulating supply and demand on a second-by-second basis to keep the AC current within the exacting required tolerance bounds [29]. As more and more renewables are connected to the electrical grid, variability in supply and fluctuations in frequency are increasingly frequent and severe. Typically, thermal units are ramped up or down to provide frequency regulating services, which is in today's market the highest value ancillary service to the grid, since it requires many generation plants to be either on standby or forced to run at capacity levels that do not use fuel efficiently, thereby increasing electricity costs [55]. Utility-scale battery storage systems can provide frequency regulation services. As opposed to conventional plants that can take several seconds to minutes to respond to system operators' instructions, battery storage systems can typically respond to such requirements within milliseconds [43].

Reserve Capacity (Spin/Non-Spin) A crucial requirement for electrical utilities, or groups of electrical utilities, is to keep the power on even if a generator goes offline. The system as a whole must not experience excessive variation in frequency and power flow even if the largest of the system's generators goes down [40]. Typically, all generating assets in the system are deliberately run with a small percentage of reserve capacity, which adds inefficiencies, extra costs and waste. Fast-acting energy storage systems such as capacitors, flywheels and batteries can be used instead for this application, allowing generators to be run closer to their rated value and lower in this way the systems marginal price.

Voltage Support: As well as regulating frequency, grid operators must ensure a certain level of voltage which requires the management of reactive power to the grid [39]. One challenge associated with this is that reactive power can only be transmitted over short distances. Energy storage systems, properly located to the electrical grid, could be used to support the system in reactive power [52].

Black Start When the entire grid is affected by a power-outage, "Black Start" resources are used to turn it back on. Challengingly, they must be able to operate without a grid connection themselves [54]. Energy storage systems with proper technical design, can contribute to start up the electrical system, this function is highly in the case of NII, where total black outs occur more often than in interconnected electrical systems [55].

Capacity firming VRE generation is characterized by variability and uncertainty. Power fluctuations in solar PV generation are mainly caused by cloud movements, and fluctuations in wind power generation are provoked by the variability of wind speed. Coupling a specific VRE generation source with a battery reduces the variability of the power output at the point of grid interconnection, thus facilitating better integration of renewables [28]. The battery storage system can smoothen the output of VRE sources and control the ramp rate to eliminate rapid voltage and power fluctuations in the grid. Further, the smoothening of generation would allow renewable energy generators to increase compliance with their generation schedules and avoid penal charges for any deviation in generation. Generation smoothening would also allow renewable energy generators to take better positions in market-based auctions for energy or capacity because it would increase the certainty and availability of round-the-clock power [55].

Reduced RES curtailment: VRE generators do not have a controllable fixed output, but a fluctuating, non-dispatchable one. Excess renewable energy generation curtailment – in times of high VRE generation and low demand – has been witnessed in some locations, resulting in a missed opportunity to integrate clean electricity into the energy mix . Grid constraints prevent transporting excess renewable energy generation to other regions leading to curtailment. Utility-scale battery storage systems are one of the solutions for reducing renewable energy curtailment. Excess electricity can be stored and then used at peak demand, when most needed [55].

3.6 Basic Metrics of Energy Storage

In order to compare the various energy storage technologies that are mentioned above there is a need to establish a set of technical and economic parameters that will lead to the suitable technology according to the needs of autonomous NII island system. The fundamental metrics used to define a storage technology for most electricity grid systems include:

1. Energy storage capacity (kWh or Ah)
2. Charge and discharge rates (kW or A)
3. Lifetime (cycles, years, kWhlife)
4. Roundtrip efficiency (%)
5. Initial capital costs (€/kW, €/kWhcap, and €/kWhlife)
6. Operating costs (€/MWh, €/kW x yr.)

For mobile systems and systems in which space is at a very high premium, the physical size (m^3) of the system may also be important, so the parameters of Energy or Power Density would be useful, but in this case is not taken into consideration as the utility storage systems are stationary [29].

Energy Storage Capacity: is the amount of energy that can be stored at a given time [kWh]. The useful energy capacity will often be less than the stated total capacity based on several factors described below. For some battery technologies, the capacity is inversely proportional to the discharge rate of the storage system. Many technologies also have restrictions on how much of the storable energy may be used. Over discharging some technologies (in particular, lead-acid batteries) can shorten their lifetime .

Charge and Discharge Rates: are measures of power (kW) indicating the rate at which energy is added/removed from a storage system. Some systems will assume an operating voltage (V) and provide the charge/discharge rates as a current in Amper (A). For many technologies, these rates will not be always constant values; in practice, they will change with how much energy is in storage and how long power has been continuously removed/added to storage. However, at a high level they can be discussed with nominal values that are representative. The charge rate is lower than the discharge rate for most technologies.

Lifetime: every storage technology has a limited lifetime. Some technologies measure lifetime according to how much they are charged and discharged (cycles), while other technologies will lose functionality due to time passing (years) and yet others have lifetimes limited by total energy throughput (kWhlife or Ahlife). As they age, most storage technologies will suffer from degraded performance.

Roundtrip Efficiency: Every storage technology will require more energy to charge than can be discharged. This loss of energy is typically expressed as a percentage known as roundtrip efficiency *(%)*, which is the ratio of energy discharged from storage to the energy input into storage. There will be some energy losses during the process of storing the energy and some energy losses when converting the stored energy back into electricity. These both contribute to the roundtrip efficiency. Roundtrip efficiency affects the costs of storage. A less efficient storage system will require more electricity to store the same amount of electricity supplied than a more efficient storage system.

Initial Capital Cost: The capital costs provided here are estimates based on professional experience and informal surveys of publicly available prices. They are intended to provide a high-level understanding of the issues and are not intended as cost inputs into a design. Costs for a specific system will vary across a wide range of factors. These factors include system size, location, local labor rates, market variability, and intended use of the storage system, local climate, environmental considerations and transport / access issues. It is important to recognize that installing storage will impose additional costs, commonly called balance-of system (abbreviated BoS) costs. These include safety equipment (e.g. fuses, current fault protection), inverters/ rectifiers, system controllers, remote monitoring equipment and supplemental sensors.

Operating Costs: Technologies require ongoing operation and maintenance to remain at peak performance. In reality, a number of factors will influence ongoing operation and maintenance (O&M) costs, including how often the storage equipment is used, ambient temperatures, handling of the equipment, adherence to the recommended maintenance schedule, quality of installation, protection from overcharging, protection from over discharging, the rate at which the equipment is cycled and the quality of the storage equipment. For simplicity, all of these factors are bundled in a typical annual cost based on the size of the equipment (€/kW x yr.) [29].

3.7 Comparison of Energy storage technologies

In order to select the suitable energy storage technology foe Greek NIIs there are many factors that have to be taken into consideration. In Table 3 are listed all the crucial parameters for comparing the different types. Except from economic parameters technical restrictions that each technology might have as well as the maturity of each storage type should also be considered, before taking the final decision.

	Lead-Acid Batteries	**Li-Ion Batteries**	**NAS Batteries**	**Flow Batteries**	**Flywheels**	**PHES**	**CAES**	**H_2**
Max Power Rating (MW)	100	100	100	100	20	3000	1000	100
Lifetime (years)	3-10	10-15	15	20	20	25+	20+	5-30
Lifetime(cycles)	500-800	2000-3000	4000-40000	1500-15000	>100.000	>50.000	>10.000	N/A
Roundtrip efficiency	70%-90%	58%-95%	80%-90%	70%-85%	85%-95%	75%-85%	45%-60%	25%-45%
Discharge time	1min-8h	1min-8h	1min-8h	hours	secs-mins	4h-16h	2h-30h	Mins-week
Capital Cost per Discharge Power [$/KW]	300-800	400-1000	1000-2000	1200-2000	2000-4000	1000-4000	800-1000	N/A
Capital Cost per Capacity [$/KWh]	150-500	500-1500	125-250	350-800	1500-3000	100-250	50-150	N/A
Levelized Cost of Storage [$/kWh$_{life}$]	0.25-0.35	0.3-0.45	0.05-0.15	0.15-0.25	N/A	0.05-0.15	0.1-0.2	N/A
Annual Opperating Costs [$/kW-yr]	30	25	15	30	15	5	5	N/A
Matturity	Mature	Commercialized	Commercialized	Demo/ Early Commercialized	Commercialized	Mature	Commercialized	Demo/ Early Commercialized

Table 3: Characteristics of Energy Storage Systems [31], [29], [2]

In the region of bulk energy storage only the technologies of PHS and CAES can provide large amounts of energy and at the same time have a reasonable installation cost. Although CAES systems are largely dependent on the fuel cost factor, that islands and energy generation in general would like to avoid in the future years. PHS systems have ability to provide bulk amounts of power for long time periods, this fact enables them to operate both as base stations and at the same be able to cover peaks of load demand when RES generation is not sufficient. Moreover, PHS stations have the ability to absorb or inject large amounts of energy in a short period of time, as a result the system operator can utilize them to cover abrupt load fluctuations. As already has been described there are several difficulties regarding topographic and geological factors at the location of the two water reservoirs that need to be installed in a sufficient height difference. Islands with low energy demand can utilize PHS systems along with RES stations, to reliably cover up to 100% of their demand, minimizing in this way their dependence on fossil fuels.

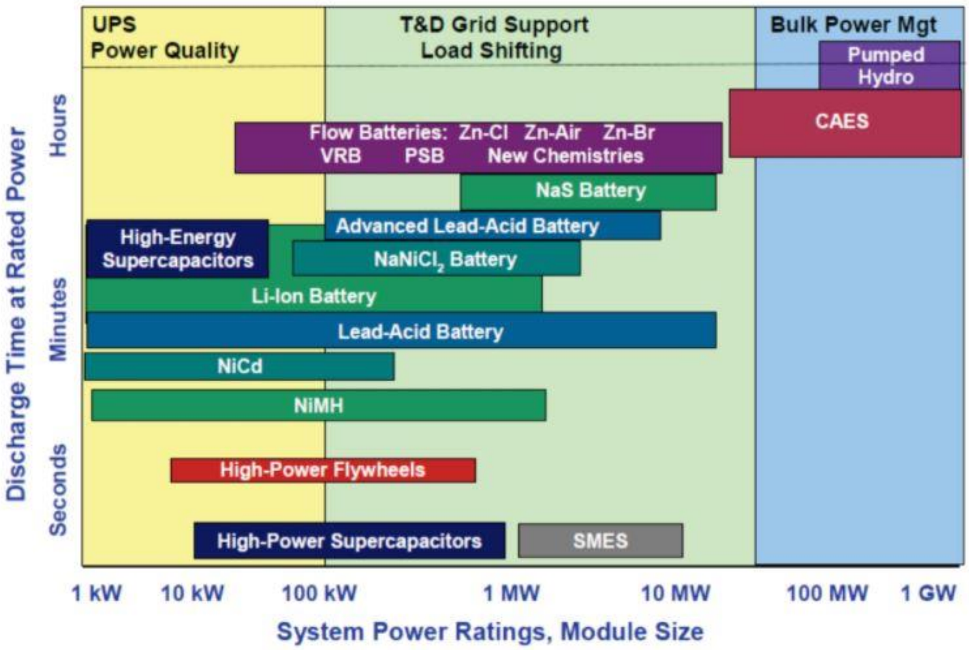


Figure 24: Discharge Power – Power Rating Diagram of ESS [31]

For smaller scale electrical grids battery storage systems suit better as they have the faster response times, a critical characteristic for grid support applications and expanding of RES penetration levels in Greek NIIs. Furthermore, easiness of installation and commercial availability, two basic factors concerning the acceptance of a storage technology. Their scalability gives the opportunity to divide on island's energy storage needs to multiple energy companies, so they provide energy storage services to the grid. As Li-Ion batteries are the most promising technology nowadays and LFP chemistry in specific is proposed for utility scale applications, this research will be focused on this battery type.

PHS and batteries are the most appropriate technologies for energy storage in Greek NIIs, as concluded from all the above reasons. In this thesis there will be investigated the application of these storage type in combination with RES, to determine the feasibility of each technology at scenarios with different scale levels.

Finally, technologies like fuel flywheels, hydrogen storage or NAS and flow batteries, positively influenced by the increased need for energy storage at the next years in the operation of islands electrical systems, may suggest promising future solutions since their current cost of storage higher than of other, more traditional systems investigated [9].

In this dissertation there will be investigated the types of battery storage (more specific the Li-Ion technology) and PHS as their characteristics suit for the case of Greek islands. More specifically, batteries may be thought more suitable for very small island cases, while PHS comprise the optimum solution for big size islands. Regarding small and medium sized island both technologies appear to be suitable, although the autonomy period and the type of application are the determinant factor for the final decision.

4 Hybrid Power stations

In this chapter, the operation policies are analysed, both for the management of HPS systems and in general for the operation of the electricity generation system on NIIs. The following description takes into consideration the existing Greek regulatory framework for HPS and NII grids and consists the basis for the generation of the algorithm, that will simulate the operation of HPS.

4.1HPS Definition and Operational Framework

The term Hybrid Power Station (HPS) refers to systems that utilizes multiple configurations of energy conversion, in order to produce energy. A hybrid system can include a conventional unit for electricity generation in combination with at least one renewable energy source, storge facilities, supervision control systems, control systems and one energy management system [41]. According to the Greek Law 3468/2006 [56], as an HPS is defined every electrical energy production station that:

1. Utilizes at least one RES
2. The total energy that is absorbed from the grid, on an annual basis, does not exceeds 30% of the total energy that is consumed in order to fill the station's energy storage system.
3. The maximum power of HPS RES production units cannot exceed the installed capacity of storage power units, increased by 20%.

Within the framework of this thesis, the term HPS refers to a station that consists of one RES (PV or wind park) and one storage facility (PHS or battery). This term is included in the previous definition.

The fundamental operating principle is the fact that energy generated by RES is stored, rather than directed injected to the grid, since the latter would reduce the penetration margin available to other existing RES stations. The stored energy can be injected later to the grid, from the storage units, in a fully dispatchable manner, preferably during peak load hours, substituting the production of thermal units with high operation cost. Hence, energy storage is not addressed as a mean to increase the efficiency of existing RES stations by reducing their energy curtailments, but as a way to install additional RES capacity in saturated island grids [56].

The fully dispatchable generation of HPS storage units (hydro turbines at PHS and inverters at battery systems) enable them to substitute not only energy but also installed capacity of conventional (thermal) units. |The provision of "guaranteed power" (i.e., firm capacity) needs to be ensured also in the case of a prolonged low wind or sunshine period, that HPS energy reserves are exhausted [27]. For this purpose, a limited amount of "grid-storage" is permitted, utilizing the energy produced from thermal units, that can be translated to a peak shaving mode of operation, transferring energy from the peak to the valley of the daily load curve. HPS energy absorption from the grid is scheduled at late night hours, when load demand is lower [57]. HPS compensation is based both on energy and capacity payments. Different tariffs are established for RES station, energy absorption and injection to the grid, these two amountς offset to the avoided or added costs by the operation of the HPS [56].

4.2HPS RES units operation

A HPS RES units can operate in one or more of the following cases:

1. Provide energy to the storage units of the HPS
2. Displace the energy that should be produced from the HPS storage units based on the grid operator program. There is an upper limit to the energy that RES units are allowed to provide to Guaranteed Power.
3. Inject energy directly to the NII grid, additional to the energy that has been utilized at cases 1. and 2.

RES unit’s top priority is to provide energy to the storage units, then to participate in the supply of Guaranteed Power and lastly to inject energy directly to the grid if the grid is able to absorb it.

In the third case, HPS has the right to inject energy to the grid only if the Island System Operator (ISO) approves it. During commitment programming the operator issues an order to define the maximum point of RES generation (set point) in real time. As long as, the rest of RES units have no restriction to inject energy to the grid, HPS can inject directly energy from its RES units, up to the defined set point.

4.3HPS Energy Storage units operation

Energy Storage units can absorb energy produced from two sources, either by HPS RES units or from the grid. The absorption schedule from RES units is carried out by the producer (HPS owner), while absorption energy from the grid is scheduled from ISO and it is obligatory from the producer to absorb the energy defined by ISO. The dispatch of HPS absorption energy from the grid is determined in order to achieve the optimal technical and economic outcome for the operation of the NII system. HPS is obliged to maintain a sufficient amount of stored energy, during the whole year, in order to ensure the safe and uninterrupted operation. The minimum amount of energy that should be stored differs for each technology of storage unit.

The operation of energy storage units is fully dispatchable, which advantages the priority of injection energy to the grid against the commitment of conventional units. HPS dispatchable units are also capable to provide Ancillary Services to the grid, which are related with the supply of active power for frequency regulation and reactive power to regulate the voltage level of the NII grid.

4.4Island Daily Generation Dispatch Schedule

Every day ISO is obliged to issue the Daily Generation Dispatch Schedule (DGDS). The program has the duration of the next 24 hours and determines the incorporation and energy production of all the island’s energy production units, RES or conventional, in order to cover the forecasted load demand, in a way complied with the safety restrictions and the operational rules of the NII .

DGDS specifies on an hourly step, for each conventional or RES units, are going to start (synchronization), stop or keep generating power. At the same time, it is calculated approximately the amount of energy that each unit is going to inject to the grid and the energy that is going to be absorbed from HPS to fill its storage systems. The main goal of the programming is to maximize the penetration of RES in the system and minimize the total operational cost of the conventional units [27].

4.4.1 HPS Dispatch

HPS submits every day to ISO an **energy offer** which declares the amount of energy that it will be available to inject in the grid at the next day. The station must provide to the grid every day a certain amount of power, **Guaranteed Energy**, which is equal to maximum energy that the storage facilities are able to provide for a predetermined number of hours. The energy offer applies for the next 24 hours and is based on the stored energy available for electricity generation and forecasts for RES generation in the next day, applying suitable safety factors. ISO has the duty to absorb the energy that is offered from HPS, within the restrictions of grid safe operation. The Hybrid Station injects the offered energy based on the program that has been specified from the operator the previous day. The grid operator has the right to modify the commitment in real time, by issuing **Allocation Commands**, in order to maintain the safe grid operation or to allow RES units to inject energy to the NII grid [27],[56], [57].

At days that HPS available energy is not sufficient to cover the Guaranteed Energy demand, absorbing energy from the grid is allowed in order for HPS to secure the provision of Guaranteed energy. In this case, HPS will issue a **load declaration** to absorb energy from the grid in the next 24 hours [27]. This additional load will increase the total demand of the system, in order to avoid excess energy production from the conventional sources. Energy absorbance, E_D, is limited to the amount of energy required to complement the available energy, E_{avail}, up to the Guaranteed energy, E_G, hence:

$$E_D = \frac{E_G - E_{avail}}{n_{rt}} \quad [27] \qquad (2)$$

n_{rt}: is the overall round-trip efficiency of the HPS storage system

E_{avail} : is the sum of HPS stored energy and the expected RES production

4.4.2 RES and Conventional Units Commitment

The management of RES and thermal units is dictated by the Operational Management Code for Non-Interconnected Islands [27], which defines a set of rules in order to ensure the safe and economic operation of the islands energy production system. Both ISO and energy producers are obliged to operate according to the rules, that are described as follows.

ISO priority is to absorb the electrical energy produced from RES (including the RES that are part of HPS), against the electrical energy produced from conventional units and at the same time reassure the safe operation of the system. Certain conventional units that exist in the system operate continuously (must run), at least at their technical minima level (small deviations are acceptable but only for a short time period), so RES priority applies in the case of these type of unit that determined for each NII. Moreover, thermal units provide ancillary services to the grid that RES are not able to offer. There is a need for a set of rules to be established that dictates the operation of the system, taking into consideration high RES penetration and safe operation. These rules should handle equally all the RES units and differentiate by the type of RES when it is justified from their technical and operational characteristics.

RES stations that are connected to NIIs electrical grids are subject to additional operational restrictions (production power restrictions), which are not implemented in large mainland grids. These restrictions are characterized "penetration restrictions" and they derive from the operation of conventional electricity production units. During the unit commitment for every allocation hour, the ISO estimates the island's ability to absorb the energy produced by RES stations, especially WF. For the described calculation, for every allocation hour *t*, the following penetration restrictions are determined:

Dynamic Response Restriction

In small NIIs grid systems, deviations in frequency occur more often, which are even more dangerous for the stability of the system in cases of abrupt loss of the total RES production, especially when it covers large portion of the load demand. Rapid increases in the wind speed, at values higher than the wind generators cut-off speed or faults in the grid lines that exceed the regulation capability of the wind generators are the main causes that induce disturbances in the system operation. At such cases the current operating conventional units are called to compensate the sudden lack of power. If the loss of RES production is big enough, this will induce deviations in the grid frequency that will lead to cut of loads.

To cope with this problem, the maximum allowable level of production for the sum of non- controlled RES production units is defined. Due to the dynamic response restriction, $P\Delta Ct$, is calculated for every allocation hour by the following relation:

$$P_{Ct} = C \times \sum_{t} P_D \quad [27] \qquad (3)$$

C: the hourly maximum penetration factor for non-controlled production RES units in the NII system

$\sum P_D$: the total maximum production power of all the units, conventional and RES, that are allocated at hour *t* in the system and is equal to the load demand

The factor of maximum penetration of wind power, C, is a characteristic of the NII system. Its value depends of the size of the NII, the type of used conventional units, the type of the wind generators and the characteristics of the system. ISO establishes the value of C=35% for large scale islands and C=30% for middle and small scale islands.

There is the possibility of reducing this percentage down to 20% for certain time periods, although the total duration does not exceed 10% of the year and they are applied only if there are serious problems to the operational safety of the NII.

Conventional Units Minimum Loading Restriction

The majority of small and middle size NII systems consists of oil units that use oil fuel (mazut) or diesel for their operation. This type of units must not operate under a certain percentage of their nominal capacity, which is known as **technical minima** and is mainly related with wearing down, increased maintenance needs and uneconomical operation, especially of diesel units. Hence the operation of such units is restricted to the boundaries defined by their technical minima and the nominal power:

$$P_{Dmin} \leq P_D \leq P_{Dn} \quad [27] \qquad (4)$$

P_{Dmin} : conventional unit's generated power

P_D : conventional unit's nominal power

P_{Dn} : conventional unit's technical minima

The technical minima of each unit depends on the age of each units and is defined individually for each unit. Common values are 30% - 50% of the nominal power for units that run on oil fuel and 25%-30% for diesel units. The calculation of technical minima restriction is conducted as follow:

$$P_{TMt} = P_{Lt} - \sum P_{Dmin} \quad [27] \qquad (5)$$

P_{Lt}: is the load of the NII system at the allocation hour *t*. This load is covered for all the production units and in it the load that it is requested from the Hybrid Station Load Demand is included.

P_{Dmin}: is the sum of technical minima of all the allocated units, conventional and RES, that are integrated in the system at the hour *t*.

ISO investigates firstly the maximum level of RES production based on the Dynamic Restriction, P_{Ct}, and then proceeds to the restriction opposed by the technical minima of production units, P_{TMt}. RES production that is possible to be absorbed for every allocation hour, based on the Dynamic Restriction, is equal to the minimum of the values of P_{Ct} and the available RES production:

$$P_{C,max_t} = \min \left\{ P_{Ct}, \sum_{RES} P_{ni} \right\} \quad [27] \qquad (6)$$

P_{C,max_t}: the maximum capability of absorbing power form non-controlled RES units, at the hour t

P_{Ct}: the maximum production from non-controlled RES units at hour t, due to dynamic restriction

$\sum_{RES} P_{ni}$: the summary of the nominal power of the island's non-controlled RES units

The second step for calculating the amount of allowable RES power, at each allocation hour t, is the implementation of the restriction that derives from the allocated technical minima. In this procedure, all the RES units are restricted proportionally in the case that their total power production exceeds the island's absorption capability, according to the relation:

$$\sum_{RES} P_{ti} \leq P_{TMt} \quad [27] \qquad (7)$$

P_{TMt}: the maximum non-controlled RES production for allocation hour t, under technical minima restriction
$\sum_{RES} P_{ti}$:the sum of the power of all the RES units in the system at allocation hour t.

ISO calculates the maximum point of production for each RES category and distributes proportionally the power production. After calculating the maximum allowable power production for each category, ISO issues an order of maximum production level (set point) in each RES unit. The order has the form of per unit of the station's maximum production power (0,00 to 1,00).

4.5 HPS Pricing Principles

In this section all the methods that are used in order to determine the tariffs based on which an HPS will be compensated are described, both for the amount of energy and services that provides to the grid or charged for the absorbed amount of energy every year. The pricing policy for the energy an HPS provides to the grid should be based on the actual avoided NII cost of operation. Likewise, the pricing policy an HPS absorbs from the grid, should be based on the NII added operation cost. Furthermore, the availability of Power Capacity is an important service that a HPS provides to the NII system, as relieves the system from the cost to extend its infrastructure, thus it should be priced accordingly [58]. Lastly, a penalty should be established if the HPS deviates from its guaranteed operation profile. This penalty price should include the added NII operational cost and the cost of developing added capacity to meet the load demand in case that HPS does not provide the guaranteed power or energy to the NII system [57].

4.5.1 Tariffs for Injecting Energy to the Grid

An HPS can provide energy to the grid either in the form of guaranteed energy or in case of RES production abundance ISO can allow PHS to inject this energy directly to the grid if there is set point excess at the examined time. Guaranteed energy can be provided from PHS controlled units or from RES production if it is available at this point of time [57]. All the above-described way of energy injection to the grid should be priced differently, below is described the methodology for each case.

According to Greek Law 3486/2006 [56] the injected energy to the grid from HPS's **controlled units** is priced based on the **average marginal production cost** of electrical energy for the peak units at the examined year. A peak unit is considered a conventional unit that operates for a time period shorter than 30% of the year. This cost is calculated including the fuel cost, operation and maintenance costs and the cost of purchasing the rights for CO_2 emissions, that accounts for the electrical energy that is substituted from HPS units during the hours of Guaranteed Energy production. The above tariff cannot be lower than the price that HPS is charged for the tankage of its storage system, increased by 25%. Additionally, according to the Greek Law 4254/2014 [59], the price of energy produced from PHS controlled units cannot be lower than the compensation of W/F, increased by 50%, to cover the energy losses in PHS storage cycle.

The electrical energy HPS RES units **injected directly** to NII grid, can offset the energy absorbed from the grid, to fill its storage system (Law 3486/2006). Especially, when RES energy **substitutes** part of the provided energy from HPS controlled units (storage units), then it is priced by 50% as energy injected from typical RES units and the rest 50% is priced as energy injected from HPS RES units. [60]

4.5.2 Charging for Energy Absorption from the Grid

The tariff of the energy a PHS absorbs from the grid is based in the average variable electrical energy production cost of the conventional base units, for the examined year. A base unit is considered a conventional unit that operates for a period longer than 70% of the year [56]. This cost is calculated including the fuel cost, operation and maintenance costs and the cost of purchasing the rights for CO_2 emissions, that accounts for the electrical energy absorbed from the grid for the tankage of HPS storage system [58].

4.5.3 Capacity Credit

The capacity credit pricing policy takes into consideration the fact that HPS substitutes not only the energy, but also the need for installed power from conventional units that should exist to the NII. The presence of a HPS in a NII allows the avoidance of an investment for a new conventional station, with respective production capacity as the examined HPS [58].

The compensation for the energy and power availability that HPS offers to the NII is calculated according to the cost that a new installed station would add to the system (Law 2468/2006). The HPS capacity credit pricing value is calculated on monthly basis as 1/12 of the following sum:

a) the annual capital cost of construction/purchase of the new conventional unit,
b) the annual standard operational cost of the new unit.

As a newly inserted station to the NII, is considered a station with conventional electrical energy production unit, constructed the year that the HPS is licensed and connected to the grid. It is important to be mentioned that not only the cost of installing a new unit to the island is taken into consideration, but also the construction cost is included, even if in several cases this solution is not very likely [56].

4.5.4 Ancillary Services

PHS controlled units are able to substitute peak or medium allocated units, that offer spinning reserve and regulate the frequency and voltage level to the NII electrical system. Thus, PHS should provide the respective ancillary services with the substituted conventional units. The amount of compensation for ancillary services is determined by the power capacity of the units to provide ancillary services, multiplied by the respective tariff, which exists for ancillary services compensation [57], [58].

4.5.5 Penalty Fee

The calculation of the penalty fee, is conducted on a annual period, based on the days that HPS did not fulfilled its obligation to ISO and the contingent load cut impacts. The amercing penalty will be enabled above a certain amount of obligation failure, a light will be imposed for cases of small deviation, while the penalty will rise proportionally to higher values in cases with significant failure [57]. For each dispatch day *d* a failure factor that represents the proportional difference between the required and offered energy to the grid is calculated.

$$\Delta d = \frac{a_d \times E_{EG} - E_{RT,d}}{a_d \times E_{EG}} \quad [57] \qquad (8)$$

α_d: the percentage of guaranteed power that is required the examined dispatch day
E_{EG}: HPS guaranteed Energy
$E_{RT,d}$: finally injected energy from HPS to the grid at the examined dispatch day *d*, during the allocation hours that is required the guaranteed power and energy
The daily failure factor Δd can take values between 0 and 1.

The next step is to calculate the average value of Δd for each period of three months, based on the number of days *k* that ISO request the total amount of guaranteed energy.

$$T = \frac{1}{k} \times \sum_{d \in k} \Delta d \quad [57] \qquad (9)$$

Finally, based on the average quarterly failure factor *Ta*, the penalty P that relates to each quarter is calculated in €/MW as follows.

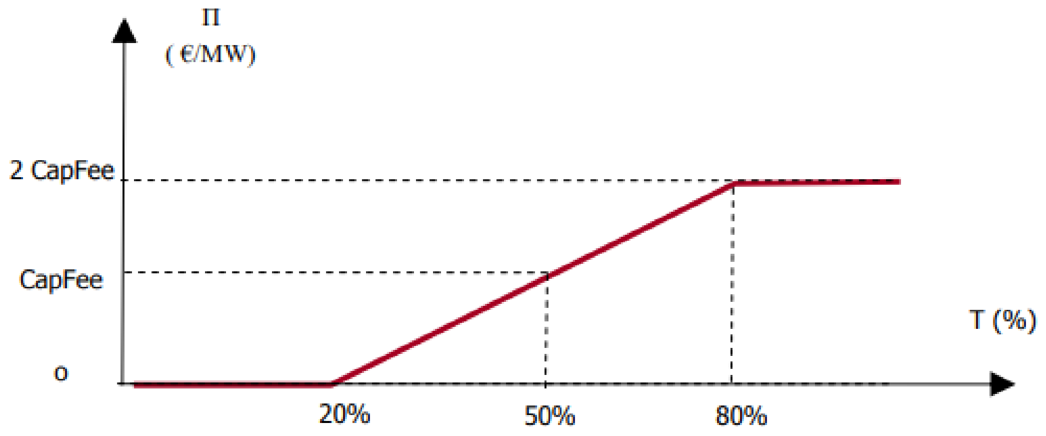


Figure 25: HPS Penalty Calculation Fee [2]

At this point it is important to be mentioned that within this dissertation the compensation for ancillary services has not be taken into consideration, as the algorithm does not represent energy system dynamic phenomena. Also, no penalty calculation is conducted, because it is considered that HPS operates without any deviations from the legislation throughout the year [57].

---

[2] Capp Fee is the Capacity Credit fee.

5 Modeling and Simulation

The simulation algorithm has been developed in the MATLAB software. In the simulation the daily dispatch program and the operation management for the non - interconnected island of Lemnos are replicated. The algorithm coordinates the operation of the already existing various energy sources, with the addition of an examined HPS, in order to meet the island's annual energy demand.

The load demand and the available energy from RES units are represented from their respected hourly time series. The time series for the load demand and the available wind energy are provided from the island's operator. The available energy from PV stations has been produced with the help of System Advisor Model, which is a dedicated simulation software platform for PV generation, both for the existing PV stations on the island and for the examined HPS PV unit. Conventional thermal units are described by their basic technical characteristics, which are, nominal power, technical minima, specific fuel consumption for various load factors, O&M cost, and start-up cost. Finally, HPS is modeled, taking into consideration the nominal power of the PV station, the nominal power and capacity of the storage system and the efficiency at charging and discharging cycles.

RES management in the island includes the allocation of both available dispatchable units like WF and HPS and non-dispatchable units, that in this case are the installed PV stations on the island. In each allocation day, HPS performs energy offers and load declarations. The algorithm considers the expected production from the rest RES stations on the island to program the dispatch schedule for the thermal units, allocating the spinning reserve at the available dispatchable units, calculates the acceptable penetration limits for WF. In cases of congestion, the algorithm implements curtailments at the energy offers from RES units (WF in this case). The simulations are based on the balance of energy and power in the electrical system. The time period of the simulation is one year and the time step is one hour.

From the simulation analytical timeseries of the energy produced from each power source that exist on the island are produced, conventional and RES, in order to meet the energy demand for every hour. Moreover, an annual report is produced, with all the energy and economic data that are related with the island's energy production system.

5.1 RES Management and Day Ahead Schedule (DAS)

In this chapter the basic principles that are used to program and manage the operation of the NII energy production system are described. RES units can be divided into two categories, the dispatchable and non-dispatchable units. As non-dispatchable units are considered the already existing PV station units on the island, while WF and HPS are considered as non-dispatchable units [27].

5.1.1 Management of PV units

PV stations have no operational restriction on their energy injection to the grid, as they are non-dispatchable units. PV stations consist a distributed energy production type of units, that are practically incorporated to the load demand. Hence, during the DAS programming, the predicted amount of PV generation is subtracted from the predicted load demand. Due to the incorporation of PV production to the load demand and the sufficient total spinning reserve of the system no added energy reserve is calculated for the energy injected from PV stations [61].

5.1.2 Management of WF units

WF stations are categorized as dispatchable units that receive orders of maximum penetration levels (set-point). Their energy injection to the grid can be curtailed by the dynamic restriction and technical minima restriction, in order to ensure the safe and stable operation of the system, as it is analyzed in the previous chapter. Concerning the dynamic restriction, the factor of maximum WF hourly penetration has been selected equal to 30%, according to the size Lemnos electrical system [27]. For the calculation of technical minima restriction for every allocation hour, the energy generated from PV station is also taken into consideration, according to the following equation:

$$P_{max} = P_l - P_{PV} - \sum_{conv} P_{D_{min}} \tag{10}$$

P_{max} : The maximum WF penetration as defined by the technical minima restriction for the allocation hour (h)

P_l : The island's energy demand for the allocation hour (h)

P_{PV}: The island's PV stations energy production for the allocation hour (h)

$\sum_{conv} P_{D_{min}}$: The technical minima sum of all the islands' conventional units that are dispatched at the allocation hour (h)

Regarding the WF energy production, Lemnos ISO provides only the timeseries of the injected WF energy to the grid, for the year 2019. For the hourly calculation of WF available energy production, the following assumption has been made, the available energy is 25% higher than the amount that has been injected to the grid. Hence, the timeseries of available WF energy is replicated by the time series of injected energy increased by 25%.

5.1.3 Management of the examined Hybrid station

HPS stations are categorized as dispatchable units that receive orders for the allocation of their energy production level. According to the NII Grid Code, the HPS issues an energy offer and load declaration at the start of each day, considering the expected energy production and the stored energy they contain, excluding the safety reserve. ISO allocates the hours that HPS will inject or absorb energy from the grid. In the algorithm a standard schedule of operation for the HPS throughout the year has been assumed, in which HPS injects energy at two 4-hour time periods throughout the day and absorbs energy at 5-hour time period during late night hours. Further details for the operation of the HPS will be analyzed on the relevant chapter below.

5.1.4 Generation Dispatch Schedule

Programming the dispatch schedule consists of selecting the energy production units that will inject energy to the system for every hour, RES and conventional, in a way to maximize RES penetration levels and cover the rest of the load demand from conventional units in the most economical way [27]. After subtracting PV production, the predicted WF production is incorporated (within the necessary limitations that ensure the safe operation of the system) and then HPS energy offers and load demand declarations are carried out. Finally, follows the commitment and economical occasion of the necessary thermal units.

Conventional units' commitment is carried out based on two criteria. Firstly, for every allocation hour the nominal capacity of the committed units should be able to cover the load demand and the required amount of spinning reserve, for the safe operation of the system. Secondly, special emphasis should be given in the technical minima of the committed units, that can not be lower that the load demand.

The amount of spinning reserve that is required, should be able to cover the loss of the biggest operational conventional unit, loss of the non-guaranteed RES energy production and the mispredictions in the RES production. During the system operation, the total spinning reserve is not necessarily equal to the sum of all the above-mentioned reserves, since the possibility from all of them to occur at the same time is very low. A good approach is to maintain spinning a reserve for injected WF production and an added amount equal to 10% of load demand, at each allocation hour [61].

$$\sum_{conv} P_{D_{nom}} \geq P_l - P_{PV} + 0.1 \times P_l \qquad (11)$$

$\sum_{conv} P_{D_{min}}$: The nominal capacity sum of all the islands' conventional units that are dispatched at the allocation hour (h)

P_l : The island's energy demand for the allocation hour (h)

P_{PV}: The island's PV stations energy production for the allocation hour (h)

The committed conventional units are loaded on equal proportions, based on their nominal capacity values [61]. Each thermal unit must not be loaded under the value of its technical minima. In any case the technical minima of the obligatory committed thermal units (must – run) cannot be violated.

$$\sum_{conv} P_{D_{min}} \leq P_l - P_{PV} - P_{WF} - P_{HPS} \qquad (12)$$

$\sum_{conv} P_{D_{min}}$: The technical minima sum of all the islands' conventional units that are dispatched at the allocation hour (h)

P_l : The island’s energy demand for the allocation hour (h)

P_{PV}: The island’s PV stations energy production for the allocation hour (h)

P_{PV}: The island’s WF energy production for the allocation hour (h)

P_{PV}: The island’s HPS energy injection for the allocation hour (h)

In cases with high RES production, there is the possibility that not all the available energy produced from RES in the same allocation hour can be absorbed from the grid, especially at time periods with low load demand. Congestion situations may occur at scenarios with high-RES penetration, not only at late night hours, but also at midday hours, when the non-dispatchable PV energy production coincides with HPS energy offers and WF available energy production. In order to manage this type of congestion situations special algorithms have been developed for RES energy curtailments and conventional units stop of operation when it is needed.

After the implementation of congestion management algorithms and the unit commitment and operation schedule of the dispatchable RES units and HPS absorption units, ISO programs the commitment of conventional units for every allocation hour, taking into consideration the low demand prediction and the required spinning reserve. The commitment of conventional units is based on the predetermined order of commitment, which is defined by ISO and reflects the economic operation of the units and their specific characteristics (reliability, oldness, etc.). In Table 4 is presented the list of the available units on the island and their technical and economic characteristics.

	LEMNOS AUTONOMOUS POWER GENERATION STATION											
A/A	UNIT TYPE	NOMINAL CAPACITY (MW)	TECHNICAL MINIMA (MW)	COMMITMENT ORDER	FUEL TYPE	SPECIFIC CONSUMPTION (kg/MWh)			FUEL COST (€/tn)	CO_2 EMISSIONS	CO_2 EMISSIONS COST	O&M COST
						50%	75%	100%		tnCO2/tn FUEL	€/tnCO2	(€/MWh)
1	SUMITOMO-NIIGATA 8L40X	2	1,35	2A	MAZUT	257.1	248.9	249.5	436,40	3.109	24,27	5,02
2	SUMITOMO-NIIGATA 8L40X	2	1,35	2B		257.1	248.9	249.5				
3	SUMITOMO-NIIGATA 8L40X	2	1,35	2Γ		257.1	248.9	249.5				
4	WARTSILA NSD18V32LN	6	3,257	1A		243.1	228.9	220.5				
5	WARTSILA NSD18V32LN	6	3,257	1B		243.1	228.9	220.5				
6	WARTSILA VASA 8R22MD	0,8	0,60	4	DIESEL	230.2	220.0	219.8	875,06	3.162	24,27	
7	MITSUBISHI S16R-PTA	1	0,637	3		225.0	216.6	215.7				
8	MITSUBISHI S16R-PTA	1	0,637	3		225.0	216.6	215.7				
9	MITSUBISHI S16R-PTA	1	0,637	3		225.0	216.6	215.7				
	SUM	**21,8**										

Table 4: Lemnos APS conventional units’ characteristics

5.2HPS Operation and internal management

5.2.1 HPS Energy Offer

The HPS submits an energy offer for the next 24 hours, based on the stored amount of energy available for electricity generation and the forecast of its PV station production applying suitable safety factors. The offered energy is allocated by the ISO according to the system’s needs and the daily load curve, in order to arrange the hourly schedule of HPS dispatchable units [27].

$$E_{offer} = E_{stored} + E_{PV,forecast} \times n_{roundtrip} \tag{13}$$

E_{stored}: the stored energy in the storage units, excluding the safety reserve)

$E_{PV,forecast}$: the expected energy production from PHS RES units

$n_{roundtrip}$: the roundtrip efficiency factor for charging and discharging the storage system

The HPS daily energy offered cannot be less than the guaranteed energy, demanded by the ISO.

$$E_{offer} \geq E_{guar} \tag{14}$$

E_{offer} : HPS energy offer

E_{guar} : HPS guaranteed energy

It has been made the assumption that HPS is obliged to provide at least the guaranteed amount of energy each day. On days that energy generation is not sufficient HPS issues load declaration, to absorb the needed amount of energy in order to fulfil the guaranteed energy demand.

5.2.2 HPS Load Declaration

If the guaranteed energy requested by the ISO exceeds the potential energy production and the stored energy of the HPS, then HPS is allowed to absorb energy to secure the provision of the guaranteed energy. In this case, HPS will submit a load declaration. To avoid excessive absorption of energy from the grid (HPS may be benefited in the case that the tariff for energy absorption from the grid is lower than the HPS tariff for energy production), there are the following limitations:

- In the case that HPS issues a Load Declaration, the energy offer cannot exceed the guaranteed energy level, required by the ISO
- The energy offer is limited to the amount of energy that will be added to the Energy Offer to reassure the provision of guaranteed energy. The absorbed energy from the grid should be analogous to the HPS storage system roundtrip efficiency and it is calculated by the equation *(4)*.

The ISO allocates the Load Declaration to the night valley of the daily load curve, in order to normalize it.

5.2.3 24-hour Operation

Since HPS issues energy offers and load declarations for DAS, ISO is programming the operation schedule for the HPS. At the schedule there are specified the hours that HPS is going to inject energy to the grid (it is also specified the amount of energy that will be injected for its allocation hour), as also the amount and time period of the energy absorption from the grid, at the days that HPS has submitted a Load Declaration the time period that guaranteed energy is going to be injected to the grid.

Guaranteed energy can partially originate from HPS RES unit (PV station), substituting the energy from the storage unit. The upper limit of RES participation in the provision of the HPS allocated energy is determined to be 15% of HPS storage unit's nominal production capacity, in the case of pumped hydro storage systems. For battery storage systems that utilize inverters in their power conversion systems, there can be implemented higher percentages of RES participation, according to their response capabilities in order to compensate for the instability or the possible loss of RES production that participates in the provision of guaranteed power [58].

There are three ways that the energy generated from HPS PV units can be utilized.

- Store the energy to the storage system
- Incorporate it to HPS programmed energy injection to the grid (direct injection that substitutes storage system production)
- Direct injection to the grid (outside the HPS dispatch schedule) with utilization of possible set point margin

HPS injects energy to the grid at peak load demand hours. According to ISO there are two time periods of peak load demand during the day, the first lasts from 10:00 until 14:00 at midday, the second starts at 18:00 and lasts until 23:00 at night. During the hours of HPS allocated energy production there are two possible states of operation:

1st state of operation: During hours that RES energy production is available, it is directly injected to the grid substituting part of the HPS guaranteed power, up to the substitution limit. The rest of HPS allocated energy injection to the grid is covered by discharging the energy storage unit. The excess generated energy that cannot be injected to the grid is stored to the storage system.

2nd state of operation: There is no available RES production, hence the programmable HPS energy production is fully covered by discharging the storage unit, to the point of depletion.

During the non-allocated production hours two states of operation are possible.

3rd state of operation: RES production is absorbed to fill the storage system. This state of operation occurs during early morning hours until 11:00 and at the time period 14:00– 18:00, PV production that is available is stored to the storage system, in order to be injected to the grid at a later time.

4th state of operation: At days that PV production is not sufficient to cover the guaranteed amount of energy, HPS absorbs the rest of the amount of energy from the grid.

Every day it is predicted the PV generation for the next day and it is determined the amount of energy that needs to be absorbed. The absorption takes place during late night hours when load demand is lower.

HPS is obliged to maintain a minimum amount of stored energy that is defined at least at 10% of the system's storage capacity or the amount of energy that is required for the HPS to provide the amount of guaranteed energy for one hour, the final reserve is selected based on the higher of the above two values.

Direct injection of energy from RES with utilization of possible margin of set point, occurs at the first state of operation, as long as there is surplus in energy production, excluding the energy utilized for the participation in the program production and the energy stored to the HPS storage system. Moreover, it is possible to happen at the third state of operation if the RES production exceeds HPS's storage unit absorption capacity.

According to RES utilization priorities, in the first reason of rejection is the HPS incapacity to store the energy due to the fullness of its storage system. The second reason is the lack of setpoint margin of absorbing the excess of HPS RES energy from the grid (set - point). In order for the excess RES energy to be rejected the above to conditions have to occur at the same allocation hour. In essence RES rejection or non-utilization can be considered as a result of poor HPS units sizing, but on many occasions is inevitable. In Figure 23 the flowcharts of the above-described algorithm are presented.

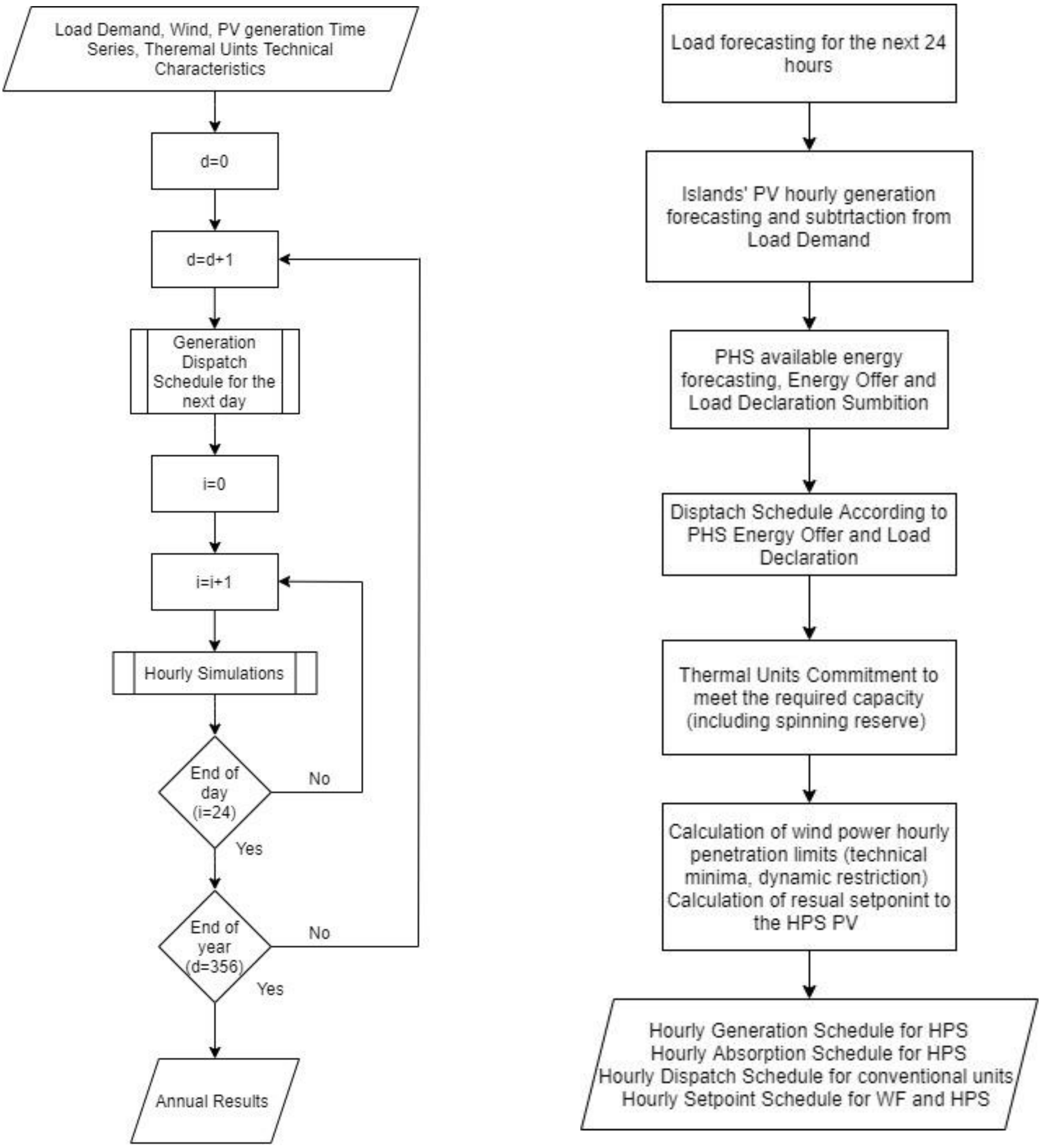
5.2.4 Operational assumptions

For the development of the algorithm that simulates the operation of an HPS at a NII system the following assumptions have been made:

- For PHS energy storage the roundtrip efficiency of the system is considered 70%. More specifically the efficiency of pumping – charging is 85% and the discharging efficiency is 85%. For the battery system roundtrip efficiency is considered 81%, charging efficiency 90% and discharging efficiency 90%.
- The capacity of the storage system is expressed directly to energy (MWh) , instead of volume units (m^3) for the case of PHS systems.
- Maintenance of the PHS units during the year is not taken into consideration. The achievable power of the units is considered equal to the nominal capacity for all the hours of the year. Furthermore, it is considered that HPS units are able to provide any power level from their technical minima until the maximum power (nominal power), meaning that operational power is not quantized and it is fully adjustable.
- PHS are considered dispatchable units, which means that their production level is guaranteed and can be fully controlled (increased or decreased) as desired by the island's ISO.
- In cases that HPS issues Load Declaration, the amount of declared energy is absorbed from the grid during five hours at night. The amount of energy is equally divided to the five hours ang the absorption period lasts from 02:00 – 05:00.

- HPS production profile is considered to be stable throughout the year. The energy offer is divided into two 4-hour time periods during the peak load hours.

The model that has been developed is based on the energy and power balance of the NII system. The investigation is focused on energy and economic values, for this reason long simulation time periods (at least one year) are demanded and simplified energy models are used, dynamic phenomena are not taken into account. In this analysis the simulation is based on an hourly step and the duration is one year.



(a) (b)

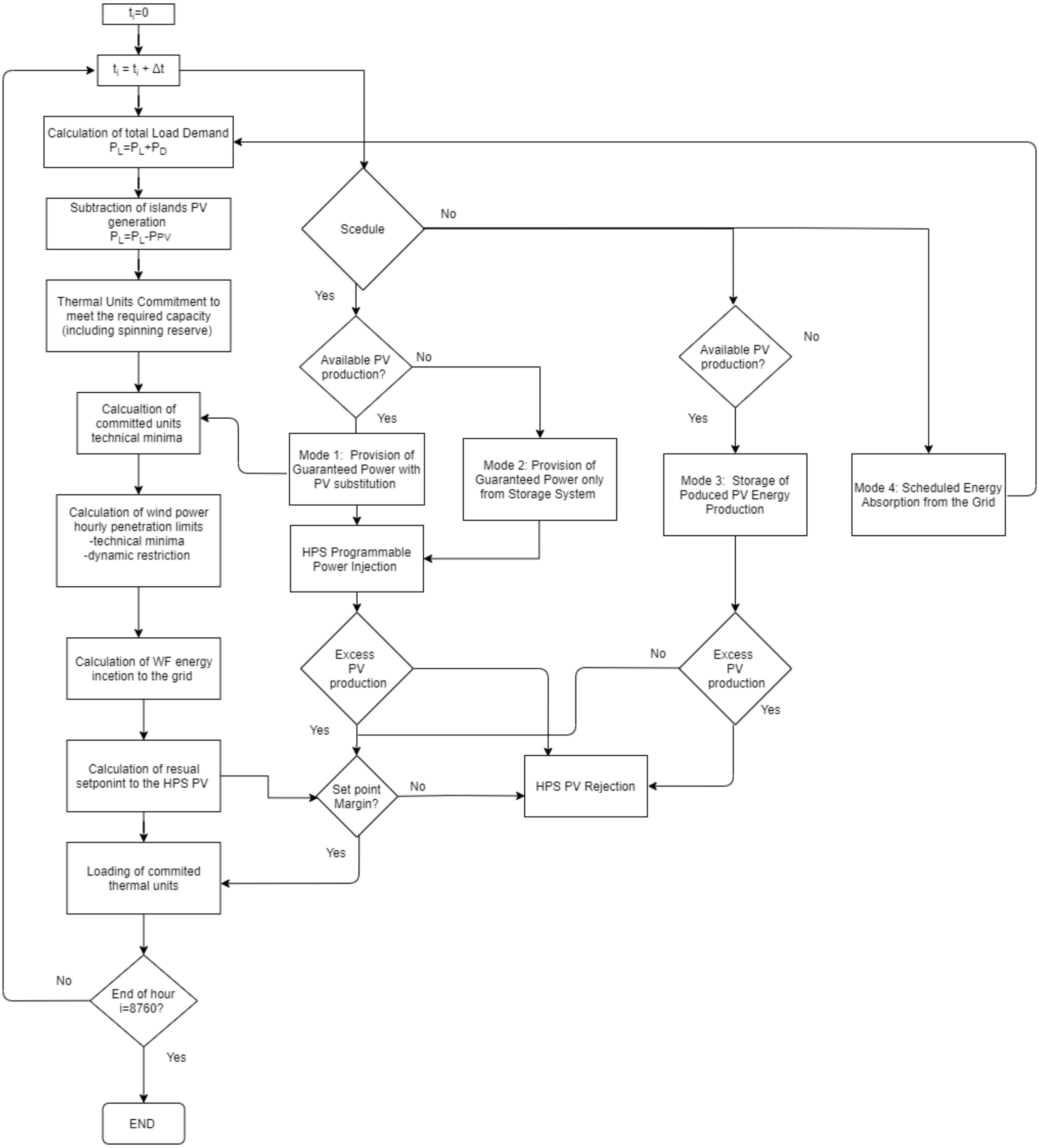


Figure 26: Flowchart of Simulation Algorithm (a) Annual Simulation, (b) Generation dispatch schedule for the next day (c) Hourly Simulation

6 Simulation Results

The simulation of the examined HPS operation is implemented on the Lemnos AEPS, the expected year that HPS will be included to the electrical system is 2023, the estimated annual load demand during this year is 65,97 GWh and the peak demand is expected to be 15,69 MW (Figure 27). According to Lemnos ISO, 2 WF with total capacity of 2,34 MW and 32 PV stations with a power output of 1,89 MW(rooftop PV are not included) are installed on the island [61].

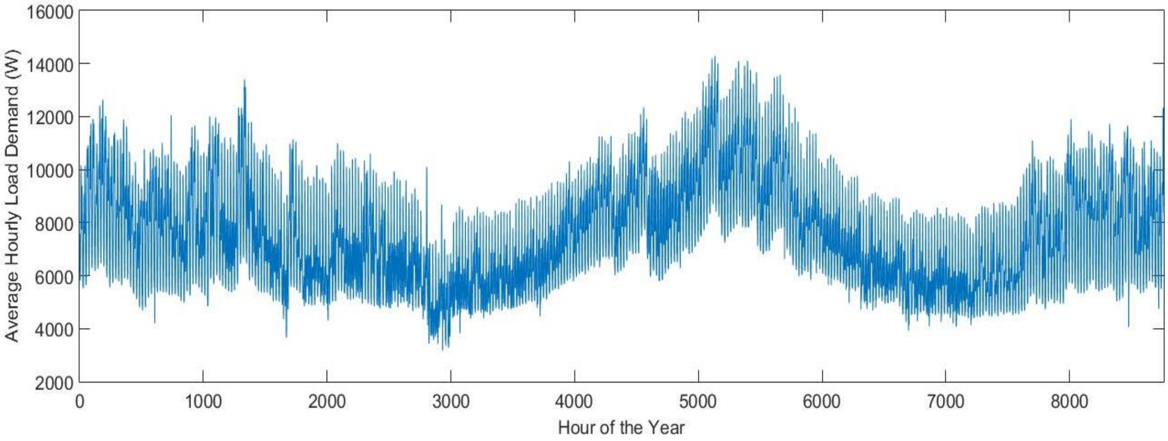


Figure 27: Annual timeseries of Lemnos load demand for the year 2023

Firstly, the simulation of the island without the operation of an HPS has been executed, in order to calculate the operating cost of Lemnos electric system, that will be used for HPS's pricing policy. Afterwards, the operation of the island will be simulated adding two different HPS stations. In both cases the HPS energy production unit will be a PV station with 4MWpk power capacity. The energy storage system at the first case will be a battery system and at the second case a PHS. After investigating the impact of the HPS operation on Lemnos electrical system, there will be a comparison between the financial viability of these two HPS types.

6.1 Island Operation Without HPS

At this section, the normal operation of the island is examined without the existence of an HPS. More specifically the energy mix on the island of Lemnos is calculated according to the regulation that has been described previously. The annual amount of fossil fuels that are consumed to cover the island's needs is also calculated. Finally, the essential parameters in order to determine HPS' pricing policy are established.

As it is presented in Figure 28, approximately 85% of Lemnos energy demand derives from fossil fuels, the rest 15% of the demand is covered from WF and PV stations. Thermal units produce a total amount of 55.84 GWh and require 8.02 ktn of mazut (since there are no diesel units committed), the amount of CO_2 emitted to the atmosphere is 24.93 ktn. Furthermore, PV stations produce 2,93 GWh of energy, whereas WF stations inject 7,19 GWh to the grid. It is important to mention that the percentage of rejected energy production from WF is 7,4% and can be characterized relatively low in comparison with other islands.

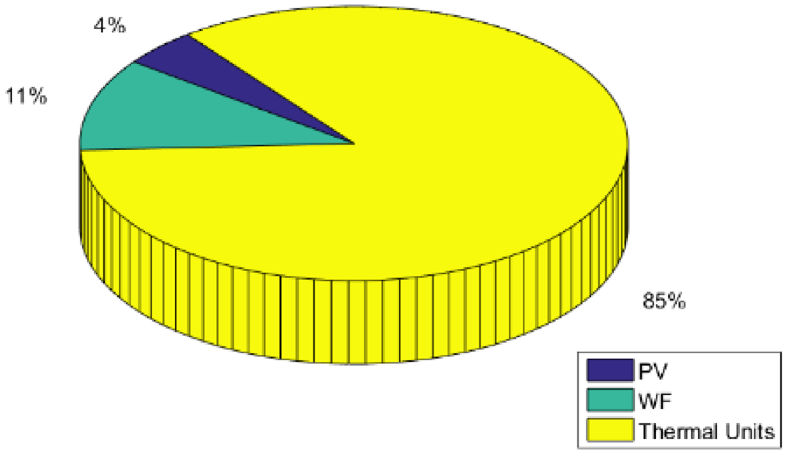


Figure 28: Coverage of Lemnos Annual Energy Demand

In Figure 28 the way that load demand is covered each hour for a typical winter and summer period is presented. As a typical winter period the first half of February (1/2-14/2) is considered while the first half of August (1/8-15/8) is considered the typical summer period. As it is depicted in the graph the vast amount of load demand is covered by the island's thermal units. Each day two load peaks occur, one during the morning hours and one in the evening. The first load peak (in the morning) is partially covered by PV production, which occurs at the same time period, while the second peak is covered mainly by thermal units. WF production is injected to the grid throughout the course of the period, during both day and night hours, although its stochastic nature is depicted in the graph, since the yellow region is not stable throughout the graph. Thermal units have two roles, as they both cover the highest amount of the island's electricity needs, while at same time the electricity production system depends on them to respond at high peaks of load demand and to counterbalance the stochastic nature of RES units.

For the determination of the variable production cost of the base thermal units and peak units the cost data given from ISO have been used, for the pricing proposal to approach the real cost of conventional energy production in Lemnos. From the simulation, for each conventional unit the operation time and the produced energy are calculated, so which thermal units are utilized as based units and which as peak units is determined. In Table 4, the island's thermal units' nominal values, their order of commitment and the specific fuel consumption are presented.

Additionally, the average annual purchase cost of mazut and diesel is 436,40€/tn and 875,06€/klt, respectively. The average annual cost of CO_2 emission rights is 24,27 €/tn CO_2, while the average annual additional cost of operation and maintenance is assumed to be the same for each unit and equal to 5,02 €/MWh. Combining all the above with the energy results from the simulation, the average annual variable cost (AVC) of base units results to be equal to **111,64** €/MWh and the average annual variable cost of peak units is **125,5** €/MWh, in both cases the fuel cost, the O&M cost and the cost of CO_2 emissions are included. The respective values for the year 2023 take into consideration the increase in the fuel price by 20%, evaluated at **129,77** €/MWh and **145,5€**/MWh. Finally, it would be helpful to compare the calculated values with the AVC of conventional units in Lemnos for the year 2019 published by the ISO, which is equal to 133,42€/MWh (including fuel cost, O&M cost and CO_2 emissions cost), so that the algorithm's calculated values can be concluded to comply with the real values.

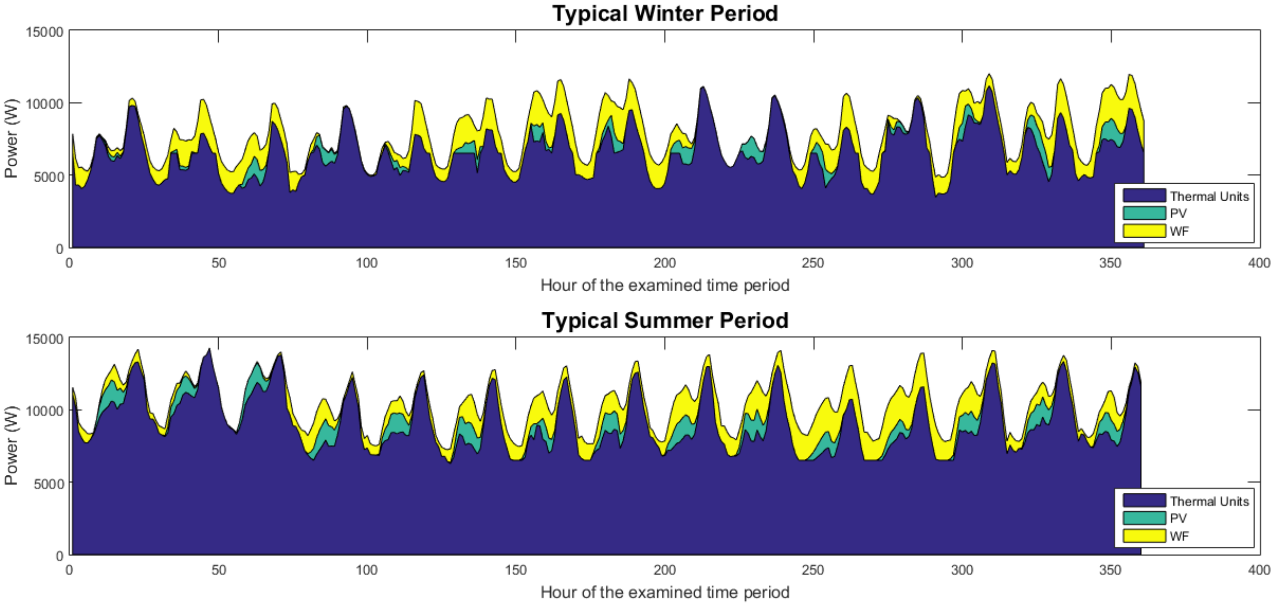


Figure 29: Lemnos NII electric production system operation for a typical winter and summer period (without HPS)

6.2HPS Energy Pricing Policy

According to the existing regulatory framework, the island's economic values for electricity production are used in order to determine the pricing policy of the energy injected or absorbed by the HPS. As it has already been described, an HPS has several ways to inject energy to the grid, so there is a need for a set of tariffs to be established for each state of operation.

Energy from HPS RES units injected directly to the grid (as long as there is a setpoint margin in this given time in the electrical system) is charged based on the current pricing for respective RES stations at NII. Throughout the current study the following prices have been used:

- **98€/MWh** for the energy produced by WF, according to Greek Law 4414/2016 [62]

- **70,37€/MWh for the energy produced by PV station**, based on the system average SMP for 2019, which is 63,98€/MWh [19], increased by 10% [63].

HPS guaranteed energy injection to the gid can derive from two possible sources, the energy storage system, and the RES unit. According to the regulatory framework the price of the energy injected to the grid from HPS storage system results as the highest of the following:

- The average variable cost of peak units, in this case it is equal to **145,5€/MWh**
- The average variable cost of base units, increased by 25%, which results at **162,21€/MWh**, taking into consideration the value **129,77€/MWh**
- The compensation tariff for WF, increased by 50%, which is :
  98€/MWh x 150% = **147€/MWh**.

Hence, the tariff for the energy injected to the grid from HPS storage system is equal to **162,21€/MWh**. The tariff for energy production from HPS PV unit is 70,37€/MWh, as the rest of the PV stations installed on the island. PV energy that is injected directly to the grid substituting the storage system guaranteed energy injection, is priced in half by the value of storage system available energy (162,21€/MWh) and the other half by the price of PV energy production (70,37€/MWh), so the outcome value is **116,29€/MWh**. The tariff for the energy that HPS absorbs from the grid is equal to the island's average annual variable cost of base units **(129,77€/MWh**).

Capacity credit compensation, results from the estimated construction cost and the standard cost of operational of a newly inserted conventional production station at the AEPS of Lemnos (annual capital and standard cost). Taking into consideration the invesment cost of 1000€/kW (according to ISO for a conventional unit that runs on heavy fuel), return on capital 8% and for an evaluation period of 20 years, the annual capital cost of a newly inserted conventional production station is equal to 101.5€/kW. The standard operational cost is equal to 47.92€/kW (standard operational cost of a conventional station in Lemnos according to NTUA study for RAE - 7/2010). Hence, the total capacity credit compensation is equal to 149.4€/kW. The proposed pricing for capacity credit compensation is **150€/kW/year**.

Guaranteed energy from HPS storage system	162,21 €/MWh
Guaranteed energy from HPS RES station (storage systems substitution)	116,29 €/MWh
Energy from RES station (penetration margin)	70.37 €/MWh
Absorbed Energy from the grid	129,77 €/MWh
Capacity Credit Compensation	150 €/kW/year

Table 5: HPS Energy Tariffs

6.3 First Scenario: PV-Battery Storage HPS

In the first scenario the operation of the island with the HPS that consists of a PV station unit and a battery storage unit is examined. Through the following figures the way that the examined HPS affects the operation of the island’s electric production system is presented. Moreover, the internal operation of the HPS is analyzed in order to gain a deeper understanding on the matter.

The HPS is designed to provide the guaranteed amount of power of 2MW for 8 hours per day, the energy will be injected to the grid in two 4-hour intervals. HPS PV unit has been sized at 4MWpk, while the storage unit has a usable capacity of 17,78MWh. The storage has been sized in order to be able to provide the guaranteed amount of energy (16MWh), also taking into consideration the discharge losses. PV unit sizing has to take into consideration two parameters as, the bigger size the unit has, the less energy is absorbed from the grid, but at the same time, the more energy is rejected, on an annual basis. With the approach that has been followed, the percentage of rejected energy from the grid is minimized (<1%), while the energy absorbed from the grid is less than the 30% limit of storage unit totally absorbed energy (PV unit and grid), that is dictated from the regulatory framework.

The time frame that HPS injects energy to the grid coincides with the peaks of the island’s load demand during the day, as it is presented in Figure 30. The energy generated from HPS lowers the peak load demand that thermal units have to cover. In this way, thermal units not only have to generate less energy, but they also have a more stable operation, as the load that they have to generate has less fluctuations. Furthermore, the fact that thermal units have to generate an extra amount of electricity, during late night hours, when the load demand would be much lower, also helps to ‘flatten’ the load curve for thermal units.

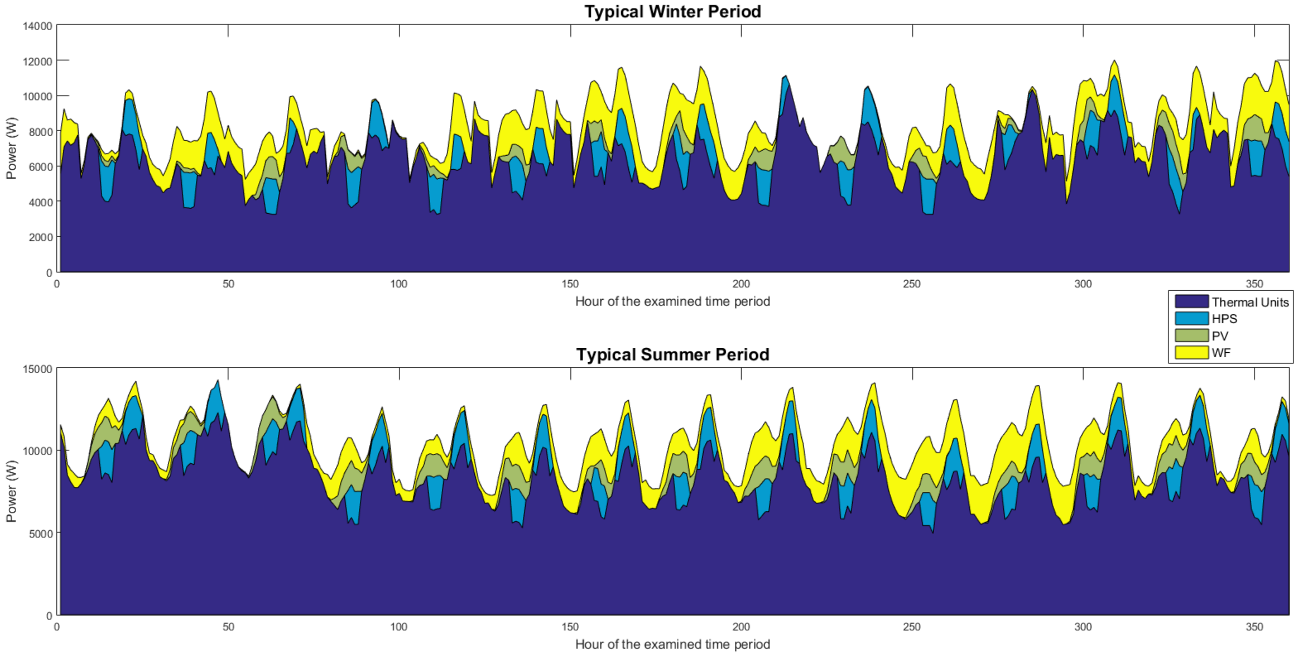


Figure 30: Lemnos NII electric production system operation for a typical winter and summer period , operation with PV-Battery HPS

Fossil fuels are also in this case the primary source of energy for the island, since 77% of the load demand is covered by thermal units. Conventional units produce a total amount of 50.98GWh and require 7.46 ktn of mazut, the amount of CO_2 emitted to the atmosphere is 23.3 ktn. There is a slight increase in the average annual variable cost (AVC) of base units, which is 131,52 €/MWh, while the average annual variable cost of peak units is 151,99 €/MWh (included fuel cost, O&M cost and cost of CO_2 emissions). Existing PV stations on the island produce 2,93 GWh of energy that covers 4% of the energy demand. The existence of the HPS slightly affects the operation of installed WF on the island, as the WF rejected energy percentage increases from 7.4% to 8%. The total amount of WF injected energy is 7,14GWh which covers 10,65% of the annual energy demand. Finally, HPS covers 9% of the energy demand by injecting 6,04GWh of energy to the grid. At this point, it is important to mention that because HPS absorbs energy from the grid, the load demand of the island is increased. In this case the annual energy demand has increased from 65,96GWh to 67,1GWh.

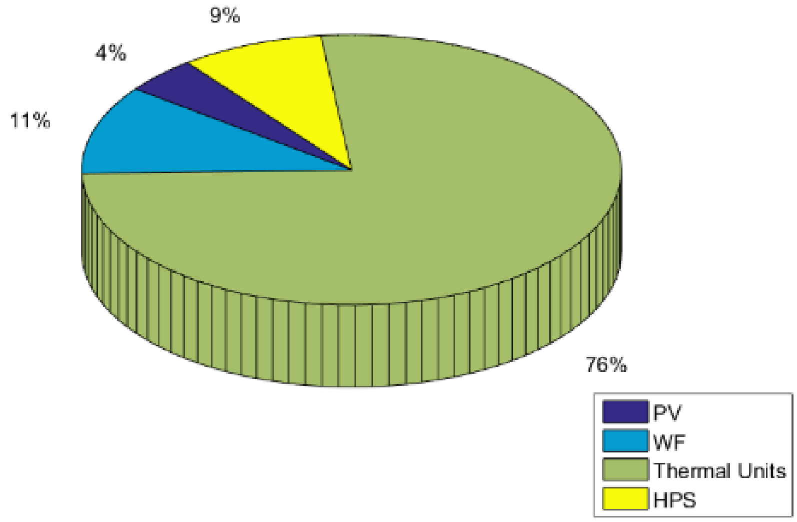


Figure 31: Coverage of Lemnos Annual Energy Demand (with PV-Battery HPS)

In Figure 32 the time series of HPS energy management for the typical winter and summer period is presented. As it is depicted in the graphs the HPS operation has many differences according to the season of the year. Firstly, energy absorption from the grid, which is presented with the azure line, occurs mostly during the winter season, while in the summer, energy production from the PV unit is sufficient to cover the guaranteed energy demand. More specifically, in summer there is surplus of generated PV energy, that can’t be stored or injected as guaranteed energy, so it is injected to the grid beyond the schedule of guaranteed energy (purple line) and in the cases that the NII electrical system is not able to absorb this energy, it is then rejected (green line). The generated amount of energy from the PV station is presented with the blue line, ain summer energy production is higher and more predictable than the winter, when weather conditions affect the energy production. Guaranteed energy is provided to the grid either from the PV unit (red line) or from the storage unit (yellow line).

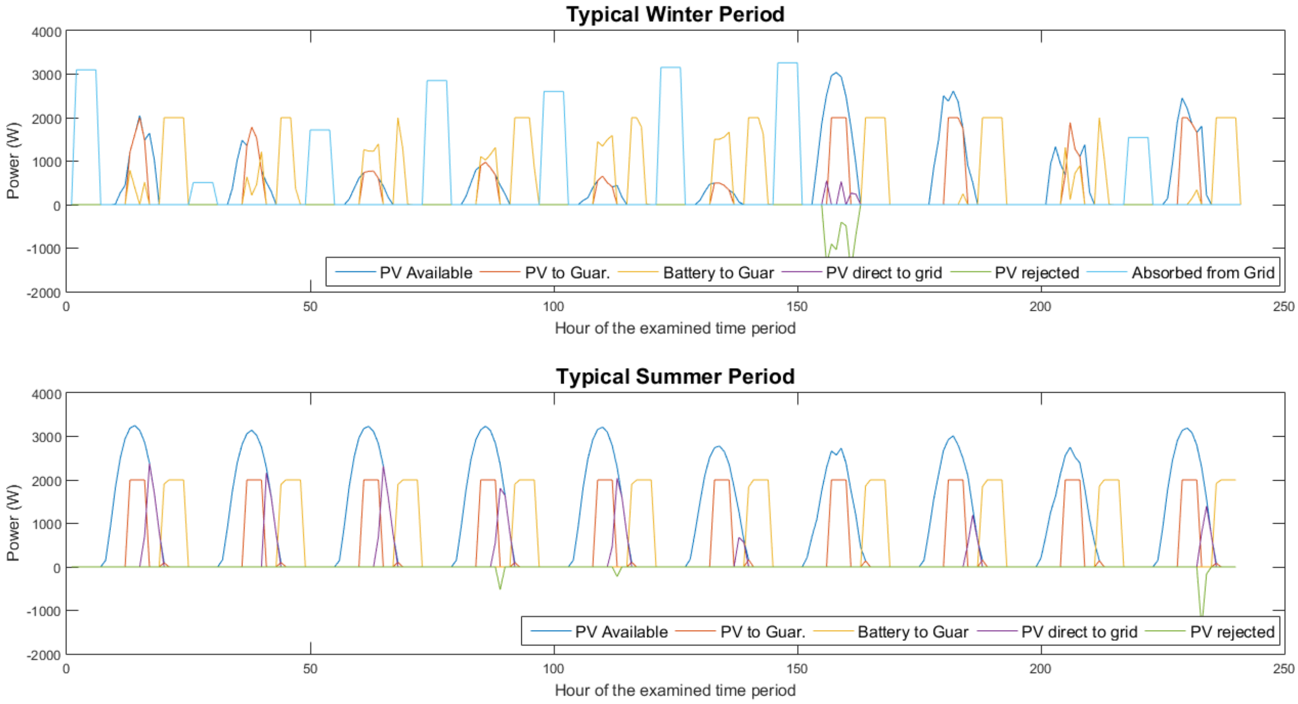


Figure 32. PV-Battery HPS operation timeseries

In Figure 33, the way that guaranteed energy is covered from the PHS two separate units is presented in more detail. In summer, when PV production is abundant, guaranteed energy is provided during the fist time period of energy injection solely from the PV unit and during the second period from the storage unit. During winter PV generation is much lower, so batteries have to inject energy during both 4-hour time intervals.

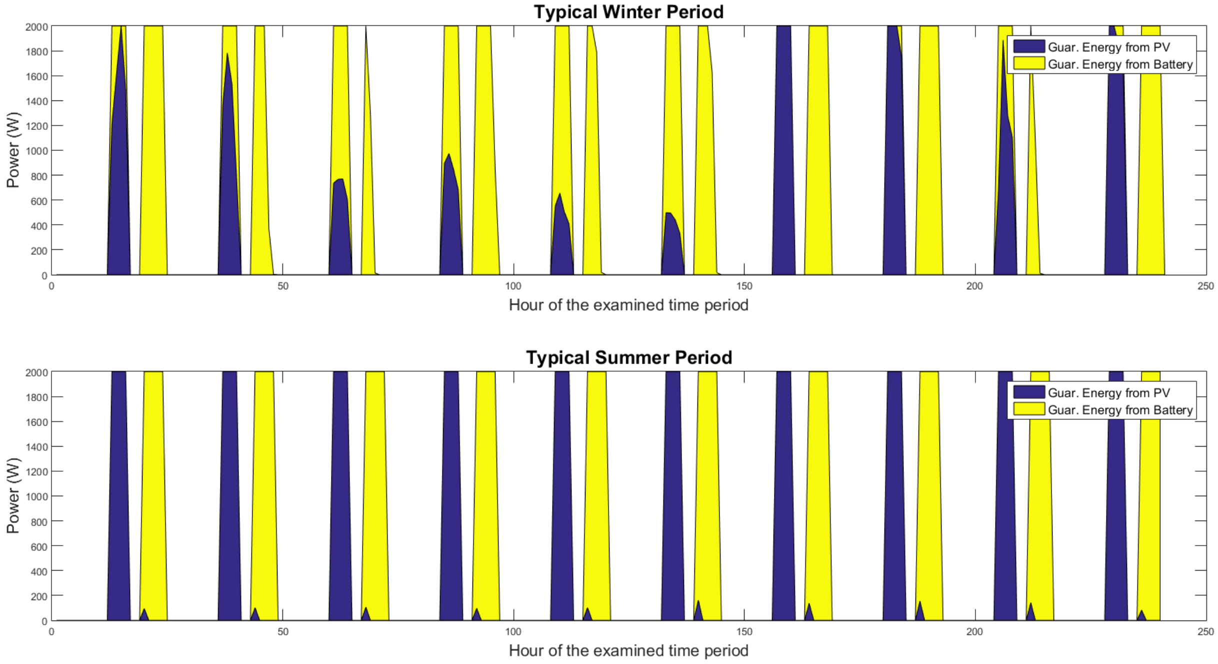


Figure 33. HPS injection of guaranteed energy

HPS PV unit produces 6,26GWh in total annually, in Figure 34 the management of HPS PV production is presented. More specifically, 2.483MWh (39,6%) is injected directly to the grid as guaranteed energy to substitute the operation of the storage system. The highest amount of PV energy production is stored to the battery system 3.209MWh (59%) so as to be injected to the grid in due time. Lastly, there is a minor amount of energy 356MWh (6%) that is directly injected to the grid beyond the schedule of guaranteed, while the rejected energy amounts to 217 MWh (3%).

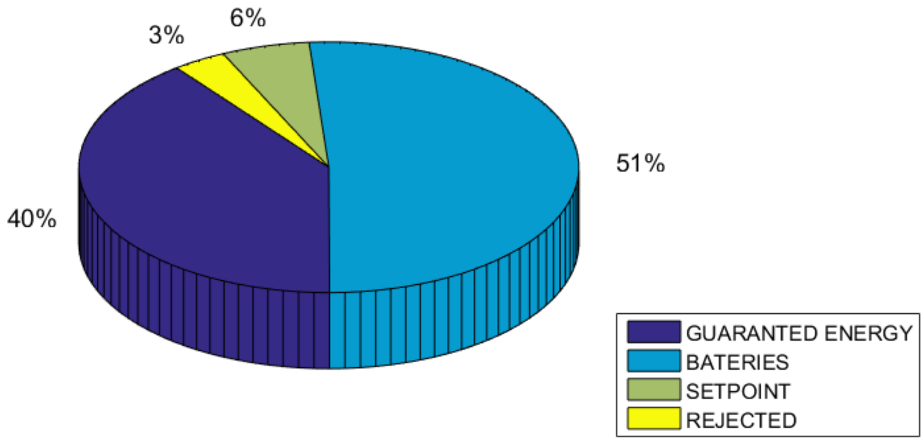


Figure 34. Management of HPS PV production

HPS absorbs from the grid 1.140MWh of energy, while the PV unit stores 3.209MWh to the battery system. Hence, the value of HPS absorption factor is 26%, which is inside the regulation limit (30%).

In Figure 35, the categories of HPS annual revenues and expenses are presented. The calculation of the presented values has been conducted according to the pricing policy that is described at the previous chapter. HPS annual net income amounts to 1.043.202 €. As it is presented in the graph, the highest amount of income comes from the injection of guaranteed energy from the batteries and the second highest from the guaranteed energy that has been substituted from PV production.

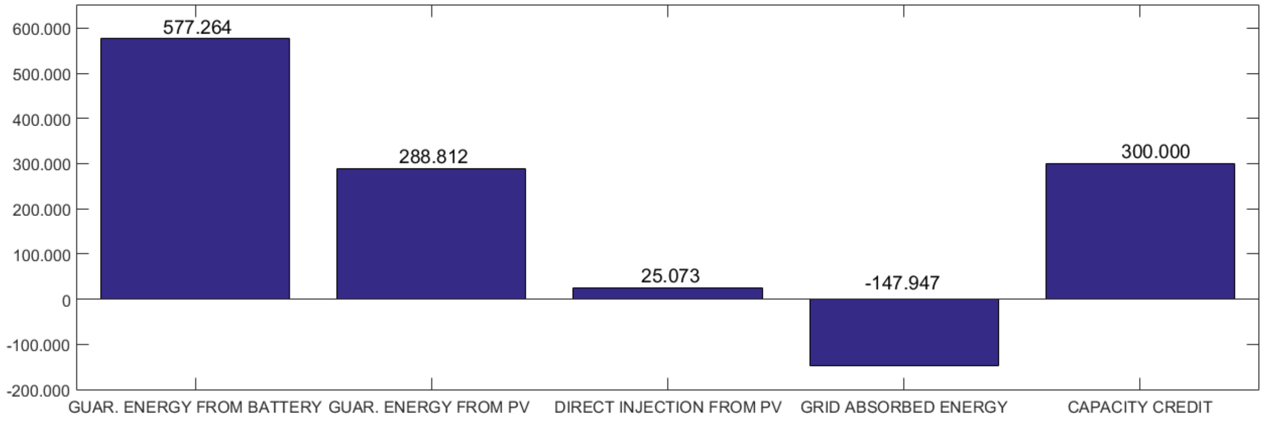


Figure 35: HPS Annual Energy Revenues and Expenses

6.4Second Scenario: PV-Hydro storage HPS

In the second scenario, the operation of an HPS with the same operational characteristics as in the previous case is examined, although this time a PHS system will be utilized as a storage unit. There are two main parameters that affect the operation of a HPS with a pumped hydro storage unit. The first parameter is related to the fact that PV unit is able to substitute the production of the storage unit, for the provision of guaranteed energy, only to the limited percentage of 15%, at this it important to mention that for the case of battery storage unit PV production could fully (100%) substitute the storage unit. The second parameter concerns the losses that occur from pumping and discharging the upper reservoir, in the simulation a round trip efficiency of 70% has been used, equally allocated to the charging and discharging cycles.

HPS is designed to provide guaranteed power of 2MW for 8 hours per day, following the same schedule as in the previous scenario. HPS PV unit has also been sized at 4MWpk, while the storage unit's usable capacity amounts to 19,04MWh, in this case the storage unit has an increased capacity, as a higher amount of discharging losses have been taken into consideration.

In Figure 36 is presented the operation of the island for the two typical time periods as in the previous case. Form the graph it can be concluded that the operation of the island is similar like in the previous case. HPS provides energy to the grid when load peaks occur, flattening the curve of load demand that thermal units have to cover.

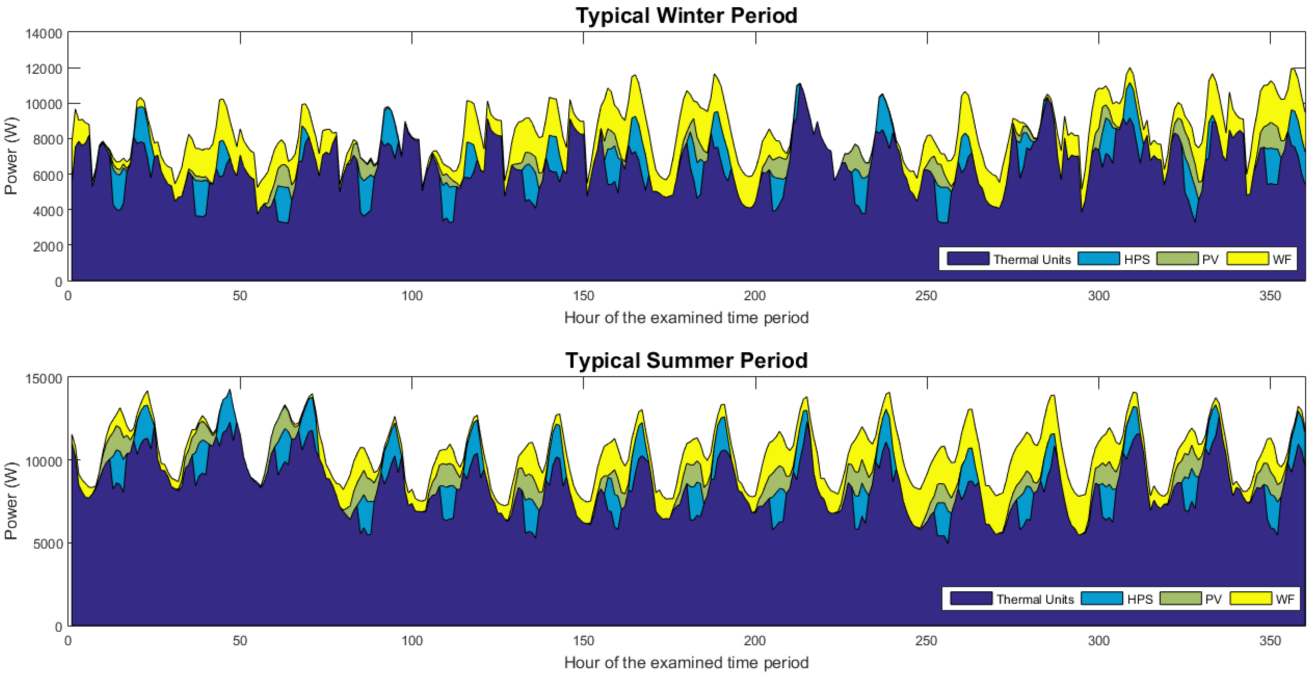


Figure 36: Lemnos NII electric production system operation for a typical winter and summer period, operation with PV-Hydro HPS

Fossil fuels are also in this case the primary source of energy for the island, as 76,6% of the load demand is covered from thermal units. Conventional units produce totally 51.57GWh and require 7.58 ktn of mazut emitting 23.57 ktn of CO2 to the atmosphere. As in the previous case, a slight increase in the average annual variable cost (AVC) of base units is present, which amounts to 131,46 €/MWh, while the average annual variable cost of peak units is 151,49 €/MWh (included fuel cost, O&M cost and cost of CO_2 emissions). Existing PV stations on the island produce 2,93 GWh of energy, which covers 4,3% of the energy demand. WF inject 7,17GWh of energy to the grid, covering 10,65% of the annual energy demand, at the same time the percentage of rejected energy is 7.4%. Finally, HPS covers 8,3% of the energy demand by injecting 5,62GWh of energy to the grid. The total amount of annual energy demand this time is 67,3GWh.

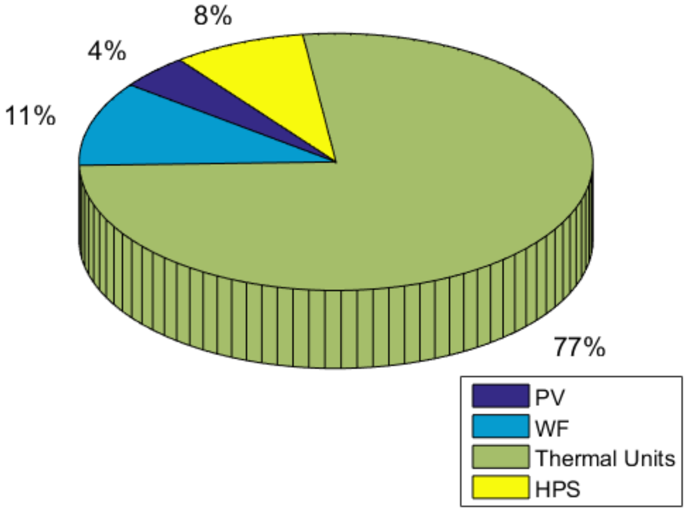


Figure 37: Coverage of Lemnos Annual Energy Demand (with PV-Hydro HPS)

In Figure 38, the time series of HPS energy management for the typical winter and summer period is presented. As in the previous case, HPS PV energy production (blue line) in the winter period is not sufficient, so the station has to absorb energy from the grid (azure line) during the night hours. During the summer period PV energy production is enough for the HPS to provide the daily guaranteed amount of energy. Guaranteed energy is provided to the grid either from the PV unit (red line) or from the storage unit (yellow line) and there will be further analysis in the next figure. One significant difference from the previous case is the absence of excess amount of PV production that can injected to the gid beyond the guaranteed energy provision schedule (purple line) or otherwise rejected (green line). Since the hydro storage system has higher charging losses, more energy from the PV unit is required in order to store the same amount of energy, so there is no PV production surplus, like in the previous case.

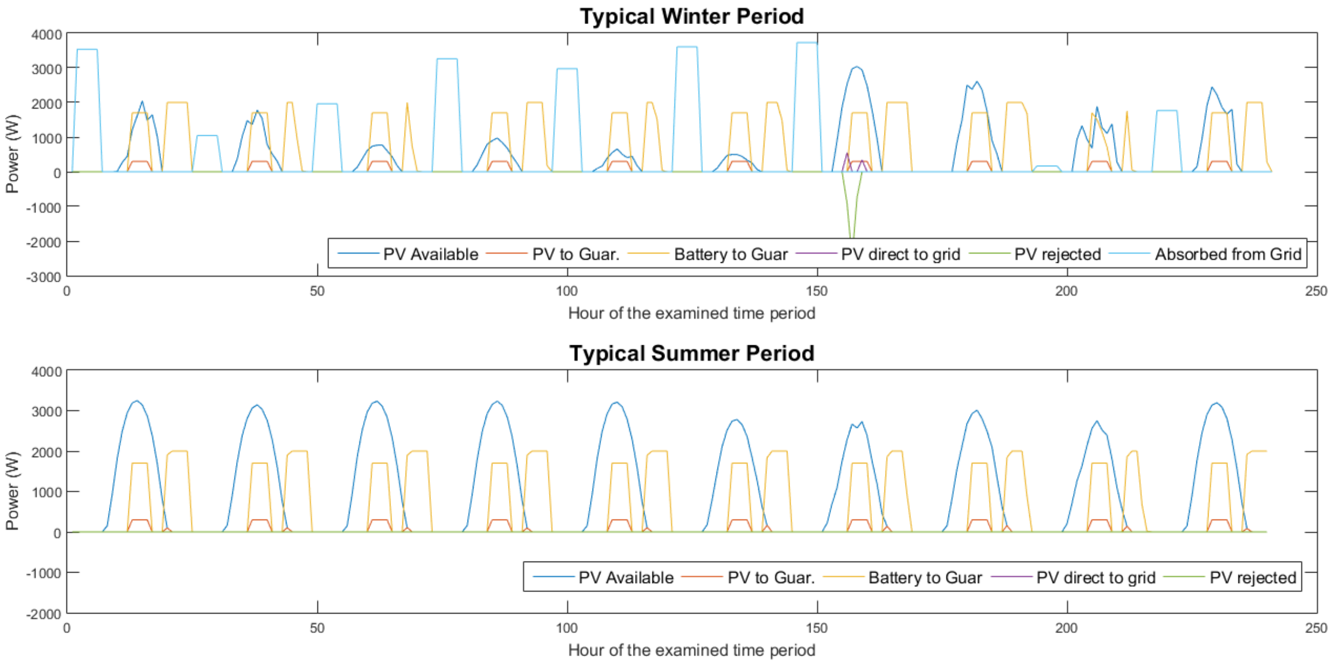


Figure 38. PV-Hydro HPS operation timeseries

In Figure 39 the guaranteed energy injection timeseries are presented. At the first time period of each day, both in summer and winter period, guaranteed power substitution from PV production is limited at 15% of guaranteed power (300kW). Furthermore, during the second time period the energy is injected exclusively from the storage unit, with an exception in the beginning of the period, only at the summer months, when the sun sets at a later time during the day.

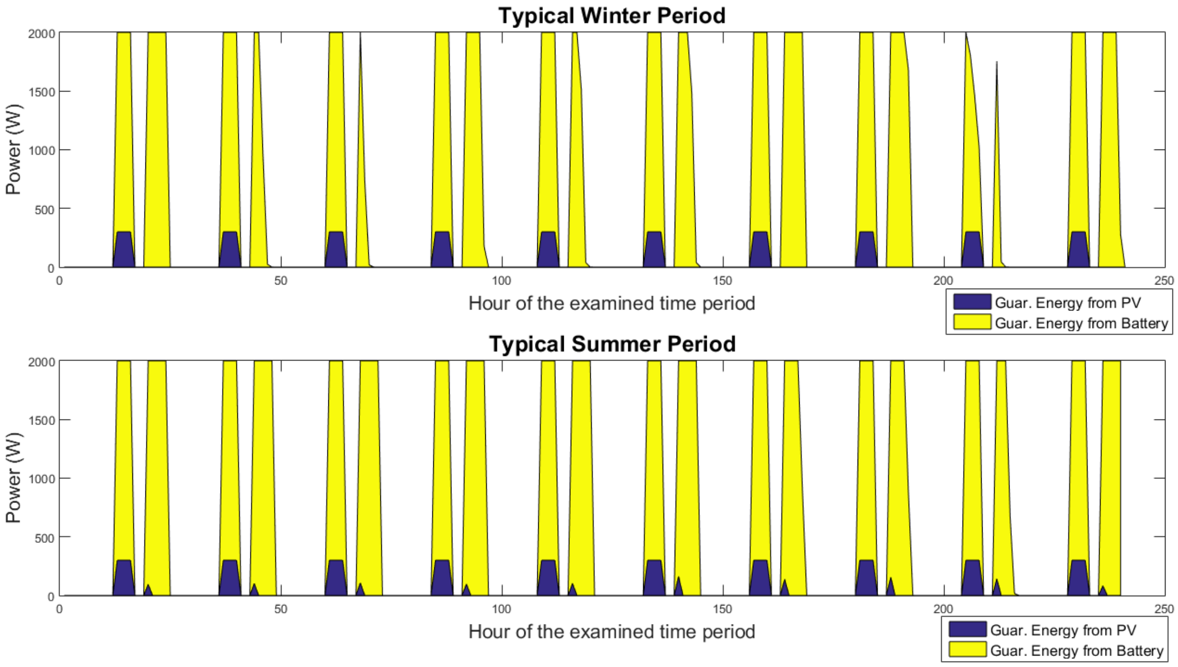


Figure 39. HPS (PV-Hydro) injection of guaranteed energy

In Figure 40 the management of examined HPS PV energy production is presented. The total annual energy production of HPS PV unit amounts to 6,26GWh. The largest highest amount of PV energy production is stored to the upper water reservoir 5.784MWh (92,3%), while the second largest amount of energy, which is 444MWh (7%) is injected directly to the grid as guaranteed energy to substitute the operation of the storage system. Lastly, a minor amount of energy 19,7MWh (0,3%) is directly injected to the grid beyond the schedule of guaranteed energy, while the rejected energy amounts to 17,9 MWh (0,2%).

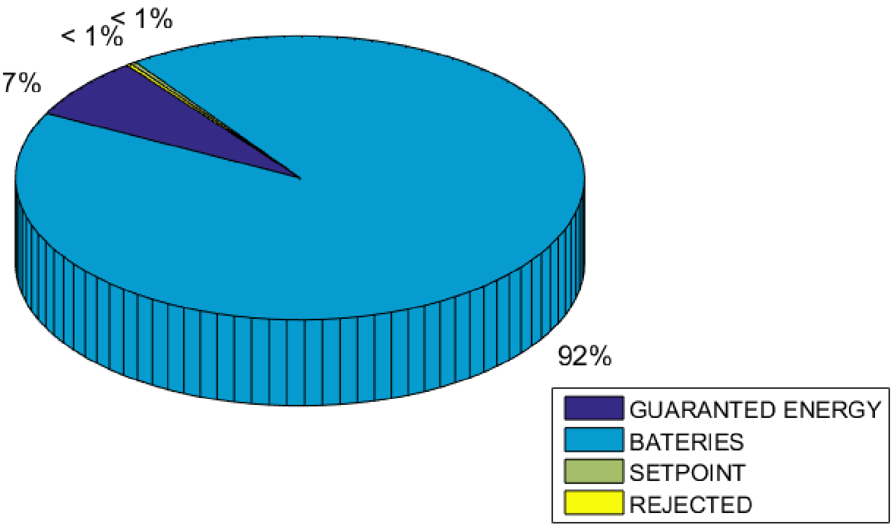


Figure 40. Management of HPS (PV-Hydro) PV production

HPS absorbs from the grid 1.334 MWh of energy, while the PV unit provides to the storage system 5.784MWh. The resulting value of HPS absorption factor is 18,7%, which is much lower than the previous case and inside the regulation limits.

Lastly, in Figure 41 the revenues from HPS operation, as well as the compensation that HPS has to pay for the energy absorption from the grid are presented. In this case the vast amount of revenues come from one source, the guaranteed energy injected to the grid, followed by the capacity credit compensation, while the revenues from PV production are much lower. The annual net income that results from all the presented energy injection or absorption categories amounts to 1.016.127 €.

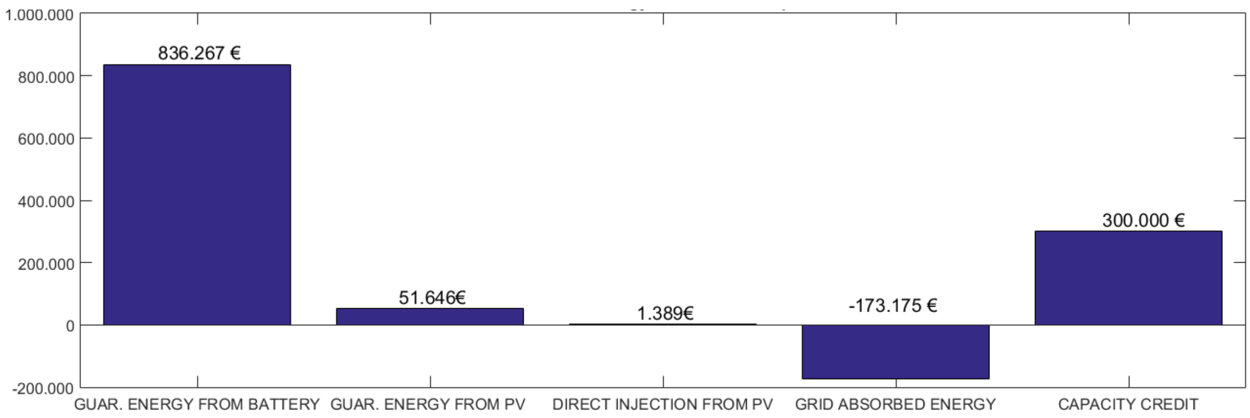


Figure 41: HPS (PV-Hydro) Annual Energy Revenues and Expenses

6.5 Comparison

A summary of all the simulation results for the total three scenarios of operation are presented in Table 6. Regarding the operation of the NII electrical system, the introduction of an HPS station helps the system to reduce its fuel consumption and CO_2 emissions. Even though the energy that HPS absorbs from the island increases the island's total load demand, the total energy production of thermal units is decreased and the waveform of the load that they have to cover is more stable, with milder peaks and more shallow valleys. PV production is not affected in any case, since the produced energy is directly injected to the grid. The operation of the installed WF on the island is slightly decreased by the presence of the HPS, although the difference is insignificant. Finally, the islands AVC is decreased in both cases, which can benefit the consumers.

Both HPS cases are beneficial to the island operation, especially in the scenario involving the battery storage unit, the cost of electricity production in Lemnos seems to reduce even more. In the first scenario the total amount of energy injected to the grid is higher, while the energy absorption from the grid is 0,2 GWh less, this can be justified from the higher charging and discharging losses in the case of hydro storage. In general, the biggest advantage of the HPS with the battery storage system is the higher percentage of guaranteed energy that can be injected directly from the PV station, as there are significantly less energy losses.

Even though that the annual net income of both HPS is roughly the same, the allocation of the revenues is different. The higher tariff of energy injected to the grid from the storage unit can compensate the difference in energy injection, so both stations have approximately the same amount of revenues. In the case of battery storage, HPS can inject to the grid a significant higher amount of guaranteed energy from the PV unit, contrary to the case of hydro storage in which guaranteed power substitution from PV is limited to 15% and 82% of the revenues come from the injection of guaranteed energy from the storage system.

			No HPS	PV-Battery Storage HPS	PV-Hydro Storage HPS
	Island Load Demand	GWh	65,96	65,96	65,96
	Total Load Demand	GWh	65,96	67,1	67,3
Thermal Units	Total Energy Production	GWh	55,84	50,98	51,57
	Load Demand Coverage	%	85	77	77,6
	Total Fuel Consumption	ktn	8,02	7,46	7,58
	CO_2 Emissions	ktn	24,93	23,3	23,57
	Base Units AVC	€/MWh	129,77	131,52	131,46
	Peak Units AVC	€/MWh	145,5	151,99	151,49
PV	Total Energy Production	GWh	2,93	2,93	2,93
	Load Demand Coverage	%	4,44	4,37	4,3
	Pricing	€/MWh	320	320	320
WF	Available energy	GWh	7,7	7,7	7,7
	Injected Energy	GWh	7,19	7,14	7,17
	Load Demand Coverage	%	10,9	10,65	10,65
	Capacity factor	%	7,4	8	7,4
	Pricing	€/MWh	95,8	95,8	95,8
HPS	Total Energy Production	GWh	0,00	6,39	5,61
	Load Demand Coverage	%	0,00	9	8,3
	Total Guaranteed Energy	GWh	0,00	6,04	5,6
	Total PV production	GWh	0,00	6,26	6,26
	PV to Guaranteed Energy	MWh	0,00	2.483	444
	PV Surplus Directly to Grid	MWh	0,00	356	19,7
	PV to Storage System	MWh	0,00	3.209	5.784
	Storage System to Guaranteed Energy	MWh	0,00	3.558	5.155
	PV Rejected Energy	MWh	0,00	217	17,9
	Absorbed Energy from the Grid	MWh	0,00	1.140	1.334
	Storage System Absorption Factor	%	0,00	26	18,7
	Revenues for Guaranteed energy from PV	€	0,00	288.812	51.646
	Revenues for Guaranteed energy from Storage Syst,	€	0,00	577.264	836.267
	Revenues from Injected PV surplus	€	0,00	25.073	1.389
	Energy Absorption from Grid Expenditure	€	0,00	147.947	173.175
	Capacity Credit Compensation	€	0,00	300.000	300.000
	Net Annual Revenues	€	0,00	1.043.202	1.016.127
	Lemnos Electrical System AVC	€/MWh	100,43	92,47	94,32

Table 6: Summarized results from the simulation scenarios

7 Conclusions

The algorithm that has been developed in the MATLAB programming software simulates the operation of a NII under normal operation and with the addition of a HPS station. The development of the algorithm is based on the island's energy balance and it is designed in a way that can be implemented to any NII electrical system, as long as the necessary input data are provided. The necessary simulation parameters are the island's load demand as well as the energy production data for conventional and RES units that are installed on the island.

After the investigation that has been conducted for the island of Lemnos, it has been proved that the introduced HPS stations help the island's electrical system to reduce the use of thermal units that cover the load demand and consequently fuel consumption and CO_2 emissions are also reduced. At the same time HPS does not affect the operation of the existing RES units on the island. Hence, HPS stations are proved to be a solution that helps NIIs to decarbonize their electricity production systems and be less dependent on imported fossil fuels.

At this study two HPS simulation scenarios have been carried out. In the first scenario the station consists of a PV unit and a battery storage unit, whereas the second station utilizes a pumped hydro as a storage unit. In both cases, the PV unit is sized at 4MWpk and the storage unit is able to store 16MWh for the provision of the guaranteed amount of 2MW for a time period of 8 hours. The size of HPS separate units has been calculated in order to minimize the amount of rejected energy produced by the PV unit and at the same time not affect the operation of the island's existing RES units.

Even though the size of the stations is similar, their operation and management of the produced energy from the PV unit has many differences. HPS with battery storage is able to provide bigger percentage of the produced energy directly to the grid as there is no limitation to the substitution of guaranteed energy from the PV unit. On the other hand, PHS has a slower response rate and for this reason guaranteed energy substitution is limited, so the vast amount of guaranteed energy is provided through the energy stored in the water reservoir, with high energy losses during charging and discharging cycles. Furthermore, the battery system provides more energy to the grid either as guaranteed energy or as a surplus of the produced energy, when the NII electrical system is able to absorb it (setpoint margin). Finally, the total amount of energy absorbed from the grid (on an annual basis), on days that PV production is not sufficient, is lower in the case of battery storage HPS. Hence, from an energy point of view, HPS with battery storage seem to prevail over HPS with pumped hydro storage system.

So far a pricing policy for HPS in the Greek energy market has not been established. For this reason a set of tariffs for the compensation of the energy that HPS injects or absorbs from the grid has been proposed, according to the relative legislation framework. The basis for the proposed tariffs is the AVC of base and peak units, calculated from the simulation of the island's electrical system without an HPS. The net amount of revenues for the two examined HPS scenarios, according to the proposed pricing policy, is almost equal. The sources of revenues are distributed differently in each case, according to the energy management in each HPS.

The development of the proposed HPS types requires further investigation of technical parameters, like the HPS response rates at dynamic phenomena in the NII electrical system, that can affect its operation. The final criterion for the installation of an HPS station, is the economic evaluation of all the aspects that are related to the construction and operation, which are affected from a wealth of parameters like the NII system or the location (especially for PHS systems) etc. From Table 3 it can be assumed that PHS have generally lower initial capital cost and operational cost per MWh than battery systems. Although, the of cost of energy storage at lithium-ion batteries is expected to decrease as the production of electric vehicles caused a radical increase in the production of lithium ion batteries, while the extended research on the field of Li Ion batteries has presented a series of promising results on increasing the storage efficiency. On the other hand, PHS systems are usually recommended for larger scale projects as their installation requires high excavation and construction cost. One last parameter that can drastically improve the operation of the NII electrical system is the ability of the HPS station to provide ancillary services to the grid, in this area battery storage systems have a clear advantage. In the near future, a realistic prediction is the implementation of a mix of these two technologies. For smaller scale islands, battery storage is ideal as it can cover the island’s restricted energy needs and at the same time provide high quality ancillary services to the grid, while for larger scale energy intense applications PHS systems is recommended.

All in all, this study has created the need for further investigation on the proposed topics below, that were not included inside this dissertation frame. Firstly, a dynamic algorithm can be created for scheduling the amount of guaranteed energy injection as well as its provision time periods inside the day, according to the island’s load demand and the RES production. Also, the algorithm can be evolved in order to be able to simulate the operation of multiple HPS stations in the same NII electrical system. Lastly, there is a need for further investigation of the energy and economic parameters that can affect the HPS operation, such as a variation in the utilization priority of HPS produced energy from RES or in the pricing policy, which can have a great impact in the results of the present study. The expected new regulatory framework and pricing policy, from the Greek Energy and Environment Ministry, can significantly affect the outcoming energy and economic results and define the economic viability of this type of investments.

References

[1] NATIONAL PLAN FRO ENERGY AND CLIMATE, MINISTRY OF ENVIROMENT AND ENERGY, ATHENS, NOVEMBER 2019

[2] Long Term Strategy for 2050, Hellenic Republic, Ministry of Energy and Environment, 2019

[3] S. Papathanassiou and N. Boulaxis, “Power limitations and energy yield calculation for wind farms operating in island systems,” Elsevier, Renewable Energy, Apr. 2006.

[4] G Gianakopoulos, N Vovos, Introduction to Electric Energy Systems, ZHTH

[5] M. Samara, Diploma Thesis: Development of Algorithms for the incorporation of Hybrid Station Electric Energy Generation in the autonomous electrical system of a Non-Interconnected Island, NTUA, Department of Electrical Engineering and Computer Science, 2014

[6] Determination of Energy Storage Requirements in Relation to Local RES Potential Characteristics for the Maximum Contribution of RES Power Generation in Aegean Island Grids, Dimitrios Zafirakis and John K. Kaldellis,

[7] Sustainable energy modelling of non-interconnected Mediterranean islands Ioannis Kougias, Sándor Szabó, Alexandros Nikitas, Nicolaos Theodossiou Aristotle University of Thessaloniki, Department of Civil Engineering, 2018

[8] IPTO, https://www.admie.gr/nea/deltia-typoy/2030-oloklironetai-o-hartis-ton-ilektrikon-diasyndeseon

[9] J. K. Kaldellis, D. Zafirakis, and K. Kavvadias, “Techno-economic comparison for energy storage systems for island autonomous electrical networks,” Renewable Sustainable Energy Rev., vol. 13, no. 2, pp. 378–392, Feb. 2009.

[10] Assessment of utility energy storage options for increased renewable energy penetration, Annette Evans, Vladimir Strezov, Tim J. Evans Graduate School of the Environment, Faculty of Science, Macquarie University, Sydney NSW 2109, Australia

[11] A Wind-Hydro-Pumped Storage Station Leading to High RES Penetration in the Autonomous Island System of Ikaria Stefanos V. Papaefthymiou, Eleni G. Karamanou, Stavros A. Papathanassiou, Senior Member, IEEE, and Michael P. Papadopoulos, Member, IEEE

[12] PPC RENEWABLES, www.ppcr.gr

[13] www.tiloshorizon.eu

[14] Papadias B.K., Analysis of Electric Energy System, Steady state Opperation, Athens, NTUA, 1985

[15] CENLEC, Voltage characteristics of electricity supplied by public electricity networks, EN 50160

[16] John J. Grainger, William D.Stevenson, Gary W.Chang, Power Systems Analysis, New York, N.Y. : McGraw-Hill Education, 2016

[17] Electrical Energy Production, System Control and Stability, K.Vournas, B.K.Papadias, K.ntelkis, 2011

[18] J.K. Kaldelis, D. Zafirakis, K. Kavadias, Techno-economic comparison of energy storage systems for island autonomous electrical networks, Renweable and Sustainable Energy Reviwes, 2007

[19] http://www.rae.gr/site/categories_new/electricity/market/wholesale/price.csp.

[20] Energy Management in the Greek Islands, Nikos HATZIARGYRIOU, Stavros PAPATHANASIOU, Isidoros VITELLAS, Stavros MAKRINIKAS, Aris DIMEAS, Theodora PATSAKA, Kostas KAOUSIAS, Antiopi GIGANTIDOY, Nikos KORRES, Eleanna HATZOPLAKI

[21] https://www.power-and-beyond.com/basics-of-an-electrical-power-transmission-system-a-919739/

[22] Prospects and challenges for clean energy in European Islands. The TILOS paradigm, J.K.Kaldellis, D.Zafirakis

[23] G.Xydis, Comparison Study between a Reneweable Energy Supply System and a Supergridfor achieving 100% from Renweable Energy Sources in islands, International Journal of Electrical Power & energy Systems, March 2013

[24] HENDO, Department of Island Management, Informative Generation Bulletin in Non-Interconnected Islands for June 2020

[25] ANNUAL REPORT OF DAS SYSTEM EXCHANGES 2019, energy exchange group

[26] Wind Energy Center:University of Massachussets, "Wind Power: Capacity Factor and Intermmittency," Amherst.

[27] Opperational Management Code for the Greek Non Interconected Islands, HENDO,3rd Edition, July 2020

[28] George N. Psarros, Optimal Management of Autonomous Electrical Systems with Storage Stations for Higher RES Penetration, PHD Thesis, NTUA, Athens, December 2019

[29] Electricity Storage and Renewables for Island Power, IRENA, May 2012

[30] Stavros Papathanasiou, Opportunities for Electricity Storage in the Greek Non-Interconnected Islands, Clean Energy Transition for the Greek Islands, 30 October 2020

[31] DOE/EPRI Electricity Storage Handbook in Collaboration with NRECA, 2016, Sandia National Laboratories

[32] On the integration of the energy storage in smart grids: Technologies and applications Dionysia Kolokotsa1 | Nikos Kampelis1 | Angeliki Mavrigiannaki1 |Marco Gentilozzi2 | Filippo Paredes3,4 | Fabio Montagnino3,4 | Luca Venezia4

[33] Handbook on Battery Energy Storage System, Asian Development Bank, December 2018

[34] A Guide to Understanding Battery Specifications MIT Electric Vehicle Team, December 2008

[35] Parker CD, Lead-acid battery energy storagesystems for electricity supply networks, J Power Sources, 2003

[36] Lead batteries for utility energy storage: A review Geoffrey J. Maya, *, Alistair Davidsonb , Boris Monahovc, Journal of Energy Storage, ELSEVIER, 2018

[37] Razelli E, Prospects for lead -acid batteries in stationary applications: competitors and new marketsfor large penetration of renewable energies, J Power Sources, 2005

[38] Parker CD, Lead Acid battery energy storage systems for electricity supply networks, J Power Sources, 2001

[39] Investire Network Investigations on storage technologies for inte4rmittent renewable energies: evaluation and recommended R&D strategy, 2003

[40] Electriccity Staorage Association, Technologies and Applications, Clafirnia, 2003

[41] Basic Principles of Hybrid Stations Operation, Management and Pricing in Non Interconnected Islands, Regulatory Autority for Energy, Greece,

[42] https://new.siemens.com/global/en/products/buildings/fire-safety/applications/li-ion-battery-storage-system.html

[43] Paul CB, Battery energy storage for utility, Sandia National laboratories, California, 1994

[44] "Guide for electric generation units from RES" C.R.E.S., Athens, 2011.

[45] https://arena.gov.au/blog/what-is-pumped-hydro-and-how-does-it-work/

[46] A. Loukatou, Diploma Thesis: Storage Technologies for Wind Power with Pumped Hydro Storage, Athens, NTUA, Department of Electrical Engineering and Copmuter Science, 2013

[47] C.Bueno, J.A Karta, "Wind powered pumped hydro storage systems, a means of increasing the penetration of renewable energy in the Cnary Islands," in Renewable and Sustainable Energy Reviews, No. 4 2006, pp. 312-340

[48] https://energystorage.org/why-energy-storage/technologies/mechanical-energy-storage/

[49] Kandiloros I, Diploma Thesis: Use of air tank at air-turbine units for Frequency regulation and Energy Storage in Electric Systems with high wind penetration-Apllication to the Rhodes Autonomous System, Athens, NTUA, 2012

[50] The effect of key parameters on the design of an optimized caes power plant M. Khalaji Assadi1, a, S.R. Shamshirgaran2 and S. Defaee Rad3, EDP Sciences, 2016

[51] Stand-Alone Microgrid with 100% Renewable Energy: A Case Study with Hybrid Solar PV-Battery-Hydrogen Furat Dawood, GM Shafiullah and Martin Anda Discipline of Engineering and Energy, College of Science, Murdoch University26

[52] Zhaoxiang; Koenig, Gary M. (12 May 2017). "Review Article: Flow battery systems with solid electroactive materials". Journal of Vacuum Science & Technology B, Nanotechnology and Microelectronics: Materials, Processing, Measurement, and Phenomena.

[53] https://byjus.com/chemistry/lead-acid-battery/

[54] Lotspeich C. A comparative assessment of flow battery technologies, Proceedings of the electrical energy storage applications and technologies international conference, 2002

[55] IRENA, UTILITY-SCALE BATTERIES, INNOVATION LANDSCAPE BRIEF, 2019

[56] “Electricity generation from renewable energy sources and high efficiency cogeneration of electricity and heat,” Greece, Law 3468/2006, Official Gazette A 1 ΄ 29/27.6.2006.

[57] BASIC PRINCIPLES FOR OPERATION, MANAGEMENT & PRICING OF HYBRID STATIONS AT NON INTERCONECTED ISLANDS, REGULATORY AUTHORITY FOR ENERGY, ATHENS

[58] STANDAR AGREEMENT OF SELLING ELECTRICAL ENERGY FROM A HYBRID STATION TO THE GRID ON NON-INTERCONNECTED ISLANDS

[59] Measures for support and development of the Greek Economy according to the gGreek Law, 4046/2012 and rest arrangements, Greece, Law 4254/2014 , Official Gazette 7.4.2014.

[60] S Papathanasiou, N Boulaxis, Hybrid Stations in Non-Interconnected Islands, Anemologia, Issue 69, Sept. – Oct. 2011

[61] TECHNICAL AND ECONOMIC DATA OF LEMNOS AUTONOMOYS ELECTRIC POWER SYSTEM, HENDO, ISLAND MANAGEMENT SECTROR, ATHENS 2020

[62] TECHNICAL AND ECONOMIC DATA OF LEMNOS AUTONOMOYS

[63] Modification of the Special Program for the Development of Photovoltaic stations at building infrastructures, Ministry Decision F1/1288/9011, Official Gazette 02.05.2013

[64] HENDO, Activating the smart and clean energy transition of NII, October 2020