POLITECNICO DI TORINO

Corso di Laurea Magistrale in Ingegneria Energetica e Nucleare

Tesi di Laurea Magistrale:

Estimation of the potential of Power-to-Power systems in remote islands in Greece

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15 ottobre 2020

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ABSTRACT

The paper proposes the analysis of the potential of a hybrid plant, based on renewable sources and coupled to a storage system, for the Greek islands not interconnected to the national electricity grid. The goal is to demonstrate that the plant is able to satisfy the energy load of these islands, making them independent from the purchase and subsequent use of fossil fuels for a whole year.

Initially, all the islands in Greece that could be interesting for being covered only by RES through the application of power to power storage systems will be identified and divided into load groups. Once the case studies have been selected, their energy producibility and relative consumption will be studied; data that will be processed through an optimization algorithm to obtain the optimal system configurations in different cases. Once the design has been defined, the system will be subjected to an economic analysis, comparing the results obtained at the current market level with a hypothetical future scenario, projecting its installation to 2030. The results will provide a definitive answer on the feasibility of the plant, giving the possibility to extend its applicability to other islands belonging to the same group as the one analyzed. The last section provides an analysis on the sustainability of the work, calculating the pollutants (CO_2, NO_x, SO_x) that the system would avoid releasing into the air through its realization.

1 BACKGROUND AND INTRODUCTION

The energy transition has been one of the most debated elements within the European strategies of recent decades. The terrestrial ecosystem has been irreversibly damaged by global warming caused by the continuous CO_2 emissions linked to human activities. The energy paradox created by the constant growth of world energy demand and the parallel need to reduce the consumption of fossil fuels, has made it inevitable to seek solutions that will satisfy the needs of humanity, while at the same time reducing air pollution. Nuclear energy seemed at first to be an optimal solution to the problem, however, in Europe, its use suffered a sudden halt following the 1986 Chernobyl accident, as well as having encountered difficulties regarding the problem of the storage of radioactive waste and the fear of the population related to the safety of the technology. The advent of renewable sources marks a turning point in the transition process. New technologies have slowly laid the foundations towards a definitive turning point in producing electricity, initially imposing themselves on the microscale (buildings, small plants), to pass in recent decades to establish themselves as a fundamental part for world energy generation, through large-scale plants (solar PV fields, wind farms, solar concentrated fields, geothermic fields). However, although renewable sources guarantee an inexhaustible source of energy (not depending on reserves such as fossil sources), clean and free; the continuous fluctuations and consequently the non-constant supply that characterizes them, considerably limit their use, preventing their complete affirmation. Recent advances in the development of ever more efficient energy storage technologies have given the definitive impetus to overcome these problems. The possibility of using hybrid systems, allows the supply of energy even when it is not directly available [1]. The Valletta Political Declaration on Clean Energy for EU Islands of 18 May 2017[1] identified EU islands as the next potential precursors in this clean energy transition, as they have greater needs [2]. In these areas, electricity production is still heavily dependent on the use of diesel and oil, which must be imported from abroad by sea or air, inevitably leading to high energy costs and problems relating to the safety of the transport of these substances. Many of the islands within the EU also have low energy consumption, making them ideal candidates for the development of alternative solutions. These are the premises that have pushed the European community and the islands as exemplars of sustainable energy systems, with the future aim of integrating technologies on the use of renewable sources and innovative storage also on the mainland.

The analysis presented focuses on the case study of the Greek islands. Greece is a nation characterized by numerous islands of various sizes and demands from the energy point of view. At the present time, the islands inhabited and not interconnected to the national electricity grid are 29, as for Mykonos, Siro and Paro the connection to the grid is expected by 2021 [3]. The energy needs of these islands are currently covered by 29 autonomous energy systems, based on heavy oil or diesel as fuels, which currently operate without a wholesale electricity market. The main producer of electricity from conventional units, in these systems, is the Power Production Corporation, which holds 93.30% of the production of the last two years [4]. The production of electricity from renewable sources covers a small portion of the total required demand (16.8%) and remains confined to the larger islands.

Many of these power plants are also privately owned, consequently leading to a continuous strengthening of the conventional energy resources of each island [4]. The first results were achieved at the beginning of 2020 within the European Horizon project which took place on the Greek island of Tilos; where the creation of a hybrid system for electricity production and storage consisting of a 800 [kW] wind turbine, a 160 [kW] photovoltaic park and a 2,4 [MWh]/800 [kW] $NaNiCl_2$ FIAMM battery for energy storage allowed to cover the energy load of the entire island for one year [5].

2 STORAGE SYSTEMS FOR ISOLATED SITES

According to the World Bank, the lack of an adequate energy supply considerably limits the standard of living of a considerable part of the population, estimating at around two billion people who live without access to electricity and in many millions those who have limited quantities or inadequate. For populations that do not fall within the scope of the distribution systems of national power plants, the only solution to be reached by electricity is to use power systems in remote areas (RAPS). In these areas, electricity generation is mainly achieved through the diesel generator, a relatively cheap technology to purchase and install, which however uses expensive diesel fuel as a fuel, also emitting significant quantities of pollutants into the atmosphere. In such a context, the most immediate solution to add electrical capacity in a sustainable way would be to take advantage of the 235 [W] of solar average radiation reaching the earth's surface. However, despite a system based exclusively on the solar source is characterized by a more environmentally friendly configuration, the high capital costs that characterized photovoltaic panels up to the last decade, have led to the preference for the installation of hybrid systems, in which part of the electricity was produced by the solar component and the remainder by diesel engines, using batteries coupled to photovoltaic panels as storage systems. In such a system the diesel generator can only run for a few hours a day, but at its optimum efficiency, minimizing fuel consumption and exhaust emissions.

A different solution was represented by using fuel cells or batteries as energy storage system. For their operation, fuel cells must be coupled to an electrolysis unit calibrated in excess of the instantaneous requirement of the load to be served, requiring the storage of the fuel produced and resulting in prices that up to 10/15 years ago made them inaccessible to remote areas. Currently, energy storage in RAPS has been provided exclusively in the form of battery banks, although their durability has been a major challenge. In the past, due to the development of acid concentration stratification within the electrolyte, battery life in photovoltaic (PV) systems has sometimes been shorter than expected. In remote areas, batteries characterized by less complexity and with minimum maintenance requirements were preferred, making the choice fall on gel ones, as they did not present stratification problems, proving suitable for installation through a partial state of charge operation. In general, valve regulated lead-acid (VRLA) batteries would also currently fit this profile, but due to acid stratification issues that have characterized the subassembly incorporating absorbent glass fiber separators and not being able to undergo to a routine gasification operation to overcome the problem, were not used.

Within this context, the REMOTE project (Remote area Energy supply with Multiple Options for integrated hydrogen-based Technologies), funded by the Horizon 2020 program for research and innovation and coordinated by the Politecnico di Torino, developed, produced and installed an innovative hybrid structure to store energy produced locally from renewable sources through a hybridization of chemical storage (hydrogen) and electrochemical batteries (Li-ion). The system allows the accumulation of excess energy produced to ensure a constant supply from renewable sources, independent of their typical intermittency, to isolated areas where the electricity grid does not reach. The project currently analyzes four sites:

- Ginostra, on the island of Stromboli.
- Agkistro, in Greece.
- Rye, Norway.
- Ambronetti, on the Italian Alps.

The proposed excess energy storage system allows this solution, green and decarbonized, to meet the required loads efficiently and reliably for isolated areas not connected to the traditional grid, with the aim of reducing energy imports and use of 95-100% fossil fuels, guaranteeing energy independence with zero emissions. Testing REMOTE in a wide range of weather and environmental conditions, from sunny southern Europe to windy, cold Scandinavia, allows to experience the system's potential as an almost complete replacement for fossil fuels. The current dependence on diesel generators, the solution adopted all over the world in the absence of a traditional grid, could be totally undermined by these hybrid storage systems based on hydrogen and batteries, also reducing auxiliary costs such as the laying of a submarine cable, the reduction of pollutants due to diesel emissions or the transport and maintenance of generators.

Taking a cue from this project, the work will evaluate the installability of the system proposed by REMOTE within the context of the Greek islands, making the results available to be used as an extension of the project itself.

3 SOURCES OF DATA AND SITES DESCRIPTIONS

The islands not interconnected to the national electricity grid have an annual electricity demand ranging from a few hundred MWh (Cerigotto) to a few TWh (Crete) [3]. Depending on whether the maximum hourly peak of power required is less than, or equal, the reference values (500 [kW], 5000 [kW], 50,000 [kW] and greater than 50,000 [kW]), the islands have been classified and grouped into four groups. Such a subdivision allows to obtain groups of islands characterized by similar properties, such as the number of inhabitants and the total annual energy required, thus making the analysis simpler to a single case study per group.

From 0 to 500 kW	Inhabitants	Year	Annual electricity demand [MWh/y](2017)	Peak [kW]
Denusa	163	2001	1.016	446
Agathonisi	158	2001	727	211
Arkoi	44	2011	375	137
Agiostrati	371	2001	1.095	340
Cerigotto	24	2019	276	94
Fanò	392	2011	645	290
Merlera	496	2011	879	378
Gavdos	150	2011	487	122

Table 1: Islands belonging to the first group

The island selected from the first group is Agathonisi, being the farthest from the mainland.

From 500 to 5000 kW	Inhabitants	Year	Annual electricity demand [MWh/y](2017)	Peak [kW]
Anafi	294	2011	1.298	571
Amorgo	1973	2011	10.710	3180
Citno	1608	2001	9.586	3440
Serfanto	1414	2001	8.680	3640
Castelrosso	492	2011	3.549	1050
Stampalia	1238	2001	7.008	2300
Symi	2895	2011	14.285	3900
Sciro	2602	2001	16266	4620

Table 2: Islands belonging to the second group

Within the second group, Sami was chosen. Although it is second to Sciro in terms of total annual demand requested, it has the most updated data in terms of population (2011). Data that will be fundamental in the calculation of the annual hourly load (see 2.2.1) and which will therefore provide a more truthful analysis.

From 5000 to 50000 kW	Inhabitants	Year	Annual electricity demand [MWh/y](2017)	Peak [kW]
Milo	5129	2011	49.181	13000
Santorini	13670	2001	181.674	46900
Sifanto	2442	2001	18.633	6390
Patmo	3047	2011	18.438	5900
Scarpanto	6511	2011	37.319	11180
Lemno	18104	2001	60.411	14600
Chio	51936	2001	210.435	45700
Samos	33814	2001	140.447	31800
Icaria	8312	2001	28.047	7439

Table 3: Islands belonging to the third group

Among the islands of the third group, Santorini is the most interesting to analyze, since despite the small number of inhabitants compared to the other islands, it has the second total consumption of electricity (181 [MWh/y]).

> 50000 kW	Inhabitants	Year	Annual electricity demand [MWh/y](2017)	Peak [kW]
Paro	12853	2001	225.755	70200
Coo	30947	2001	382.075	98200
Rodi	115490	2011	836.397	206700
Lesbo	90643	2001	299.860	67050
Creta	623065	2011	3.027.253	655100

Table 4: Islands belonging to the fourth group

The technology under analysis has never been studied for islands of such large dimensions and with such high loads. For this reason, the last choice was Lesbo, being the one that requires the lowest annual energy consumption.

The location of the selected case studies is shown in the following figure.

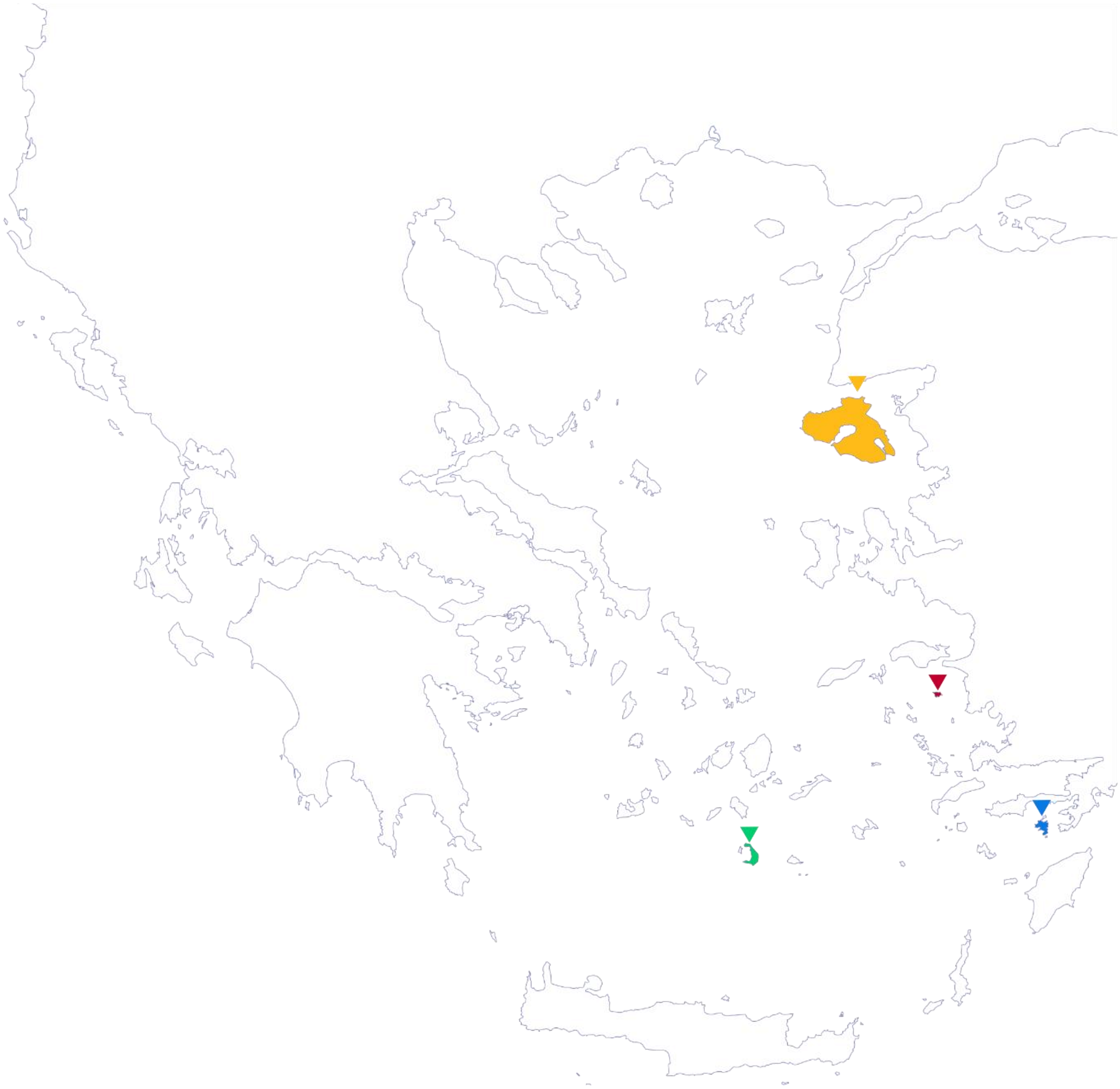

Figure 1: Localization of the case studies

3.1 SITES

Once the islands to be analyzed have been selected, it is important to know the current technologies used for electricity production. Excluding Lesbo, which has a percentage of energy generated from renewable sources equal to 15.68% [3], the remaining islands cover their energy load exclusively through diesel engines in conventional thermal cycles.

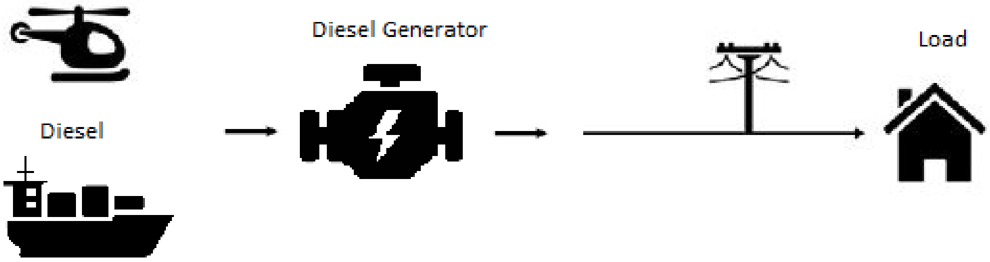

Figure 2: Current solution for electricity generation

In order to analyze the potential of a future hybrid system based on photovoltaic panels and wind turbines, it is important to know the potential that these sites offer in terms of wind speed and solar irradiance. The data was obtained from the PVGIS (Photovoltaic Geographical Information System) software, made available by the science and knowledge service of the European commission [2].

3.1.1 AGATHONISI

Located in the Dodecanese archipelago, the island of Agathonisi covers an area of about 14 [km^2], hosting about 158 residents according to the 2001 census. The main activities of the local inhabitants are related to fishing, livestock and tourism; the latter present especially in the summer months as every year the island hosts hundreds of tourists [6].

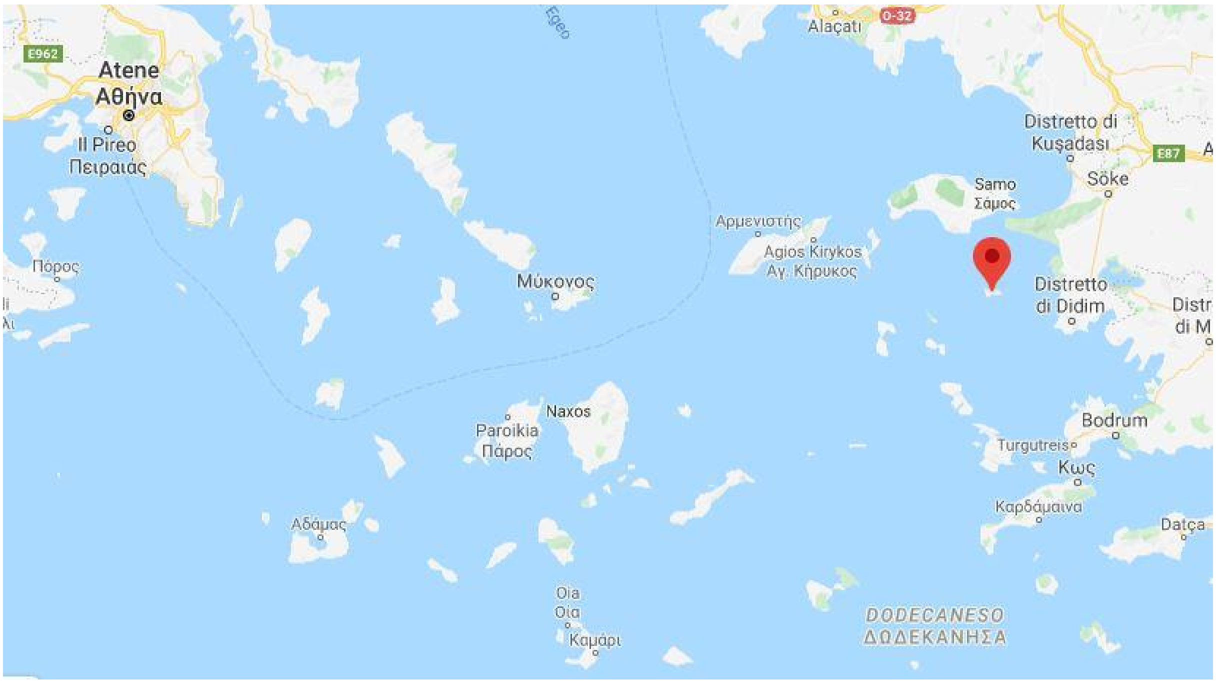

Figure 3: Agathonisi [1]

The island currently relies on diesel engines, with a total installed power of 500 [kW], to produce electricity. This technology leads to an average cost equal to 891,38 [€/MWh] [7]. The high price of energy, combined with the data obtained on wind speed and solar irradiance throughout the year, make the island a perfect candidate for the search of an alternative solution free from the use of a fossil source.

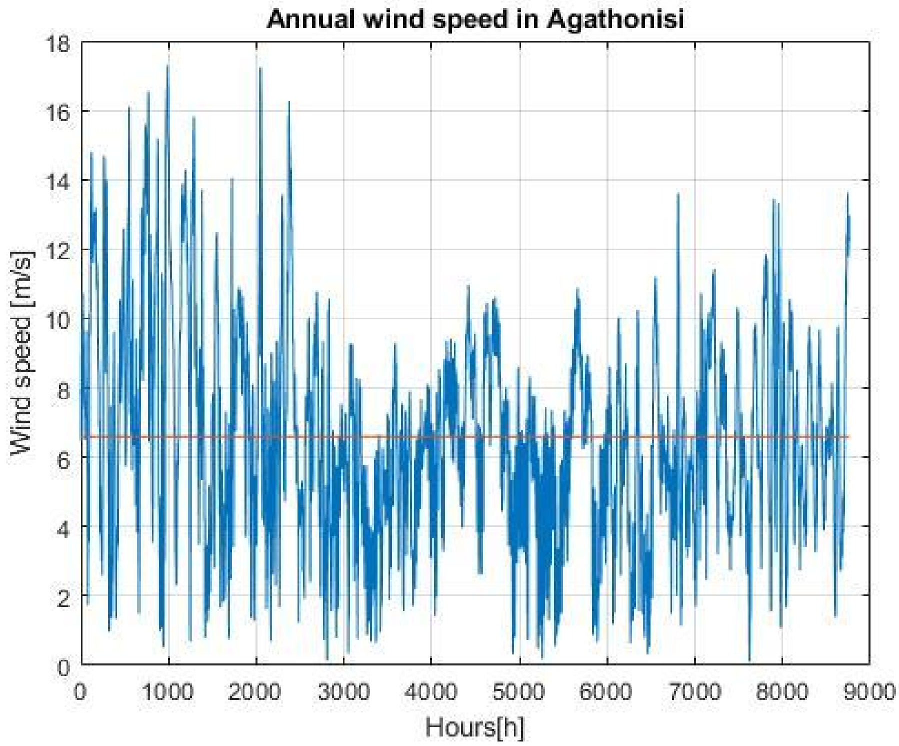

Figure 4: Annual wind speed at 10 m in Agathonisi

The wind speed trend during the year reaches peaks of almost 18 [m/s], maintaining an average speed of about 6,4 [m/s]. This value allows the installation of a hypothetical wind system. The trend of solar irradiance makes it possible to study the installation of a future photovoltaic system on the island.

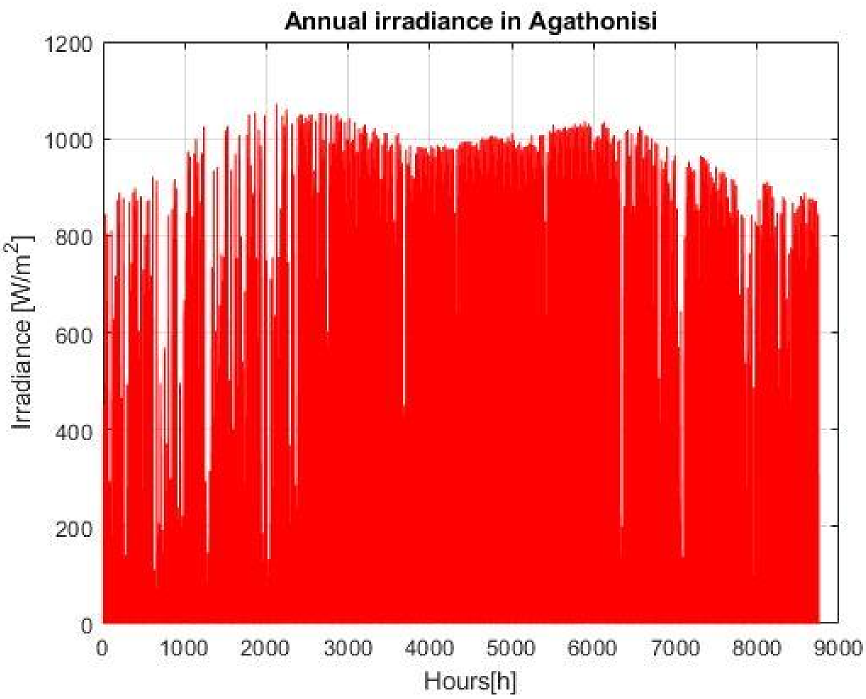

Figure 5: Annual solar irradiance in Agathonisi

3.1.2 SYMI

The island is located a few kilometers from Turkey, in the easternmost part of the Dodecanese archipelago, extending for 58,1 [km^2] [3]. As for Agathonisi, the inhabitants of the place (2580 according to the 2011 census) carry out fishing and livestock farming activities.

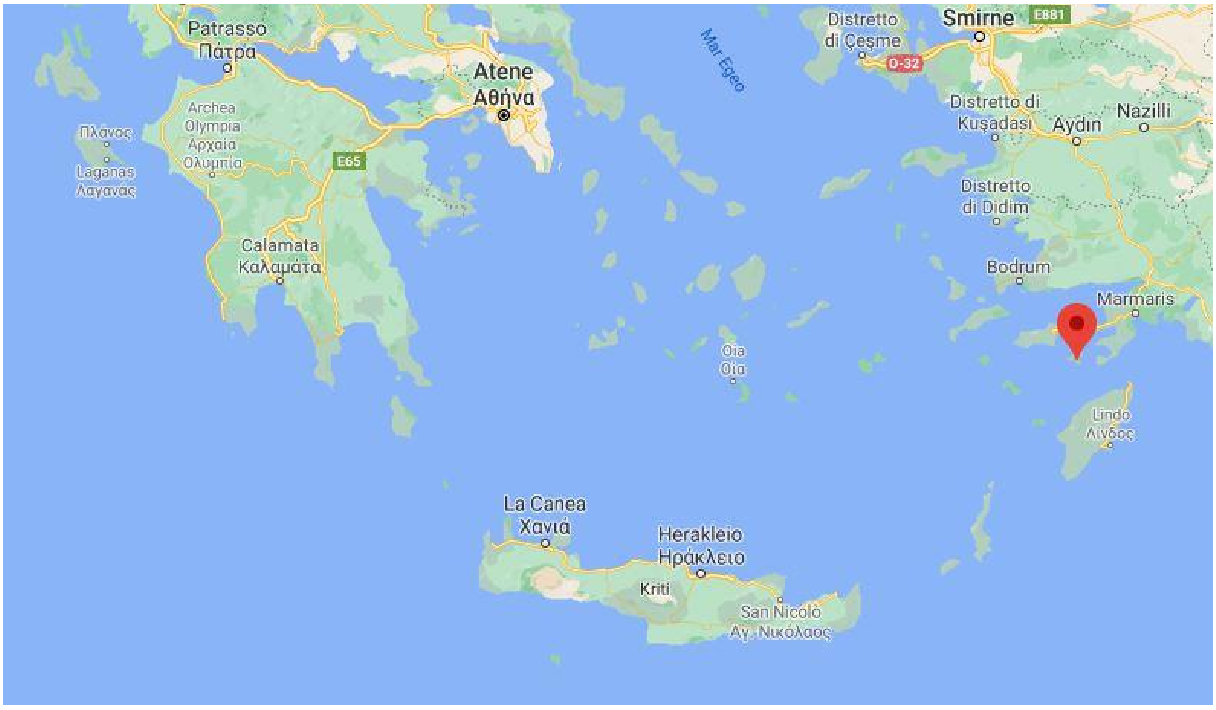

Figure 6: Symi [2]

However, the main source of income of the island is tourism. It is estimated that in the months from June to September the place hosts tourists up to five times the population. During the summer the energy demand grows considerably. The load is satisfied through a plant that uses a thermal cycle based on diesel engines, which operates with imported diesel oil. This technology leads to an average cost for the generation of electricity equal to 386,36 [€/MWh] [8], making a search for an alternative and less expensive solution inevitable.

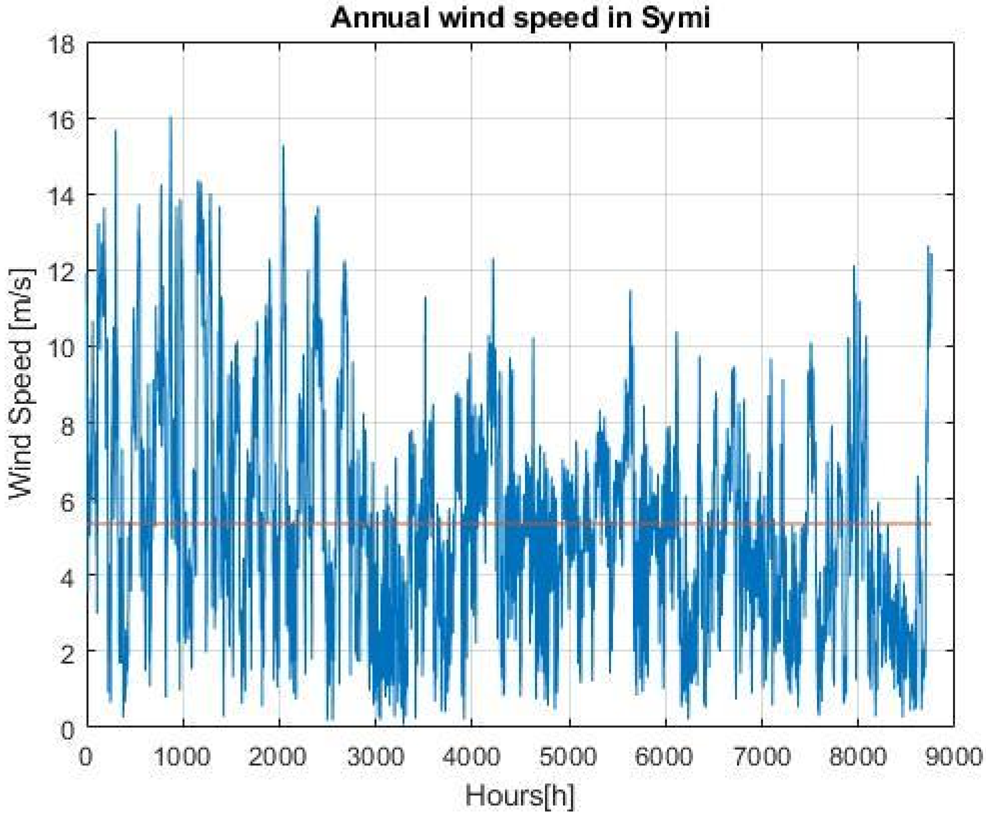

Figure 7: Annual wind speed at 10 m in Symi

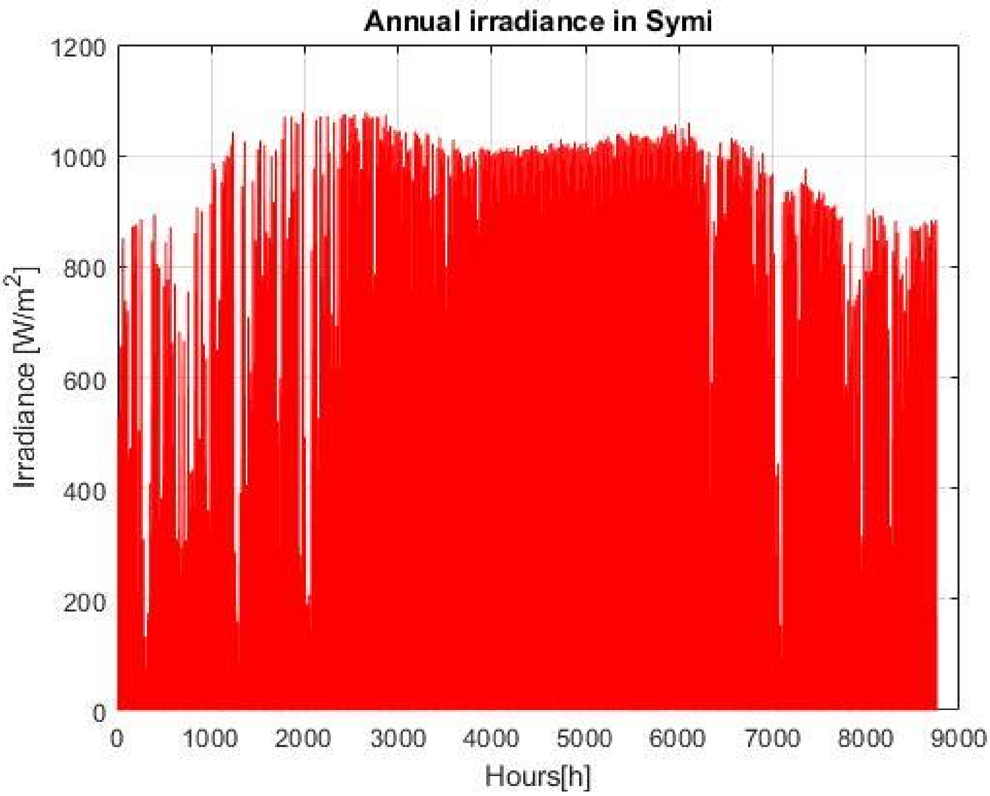

Figure 8: Annual solar irradiance in Symi

Symi is characterized by slightly lower wind speed peaks than the previous island (16 [m/s]), while maintaining an average annual speed of 5,6 [m/s] which guarantees a potential installation of a wind farm. The data on irradiance shows that the installation of a photovoltaic field could allow the island to take its first steps towards energy independence from fossil sources.

3.1.3 SANTORINI

Belonging to the Cyclades archipelago, Santorini is one of the most famous islands in Greece. Following a volcanic eruption in 1600 BC, the morphology of the island was irreversibly changed, leading to the formation of a mountain range that runs through the entire island and limits the emergence of new settlements. In fact, although the island has an area of almost 80 [km^2], its population counts only 13670 inhabitants (2001) [4].

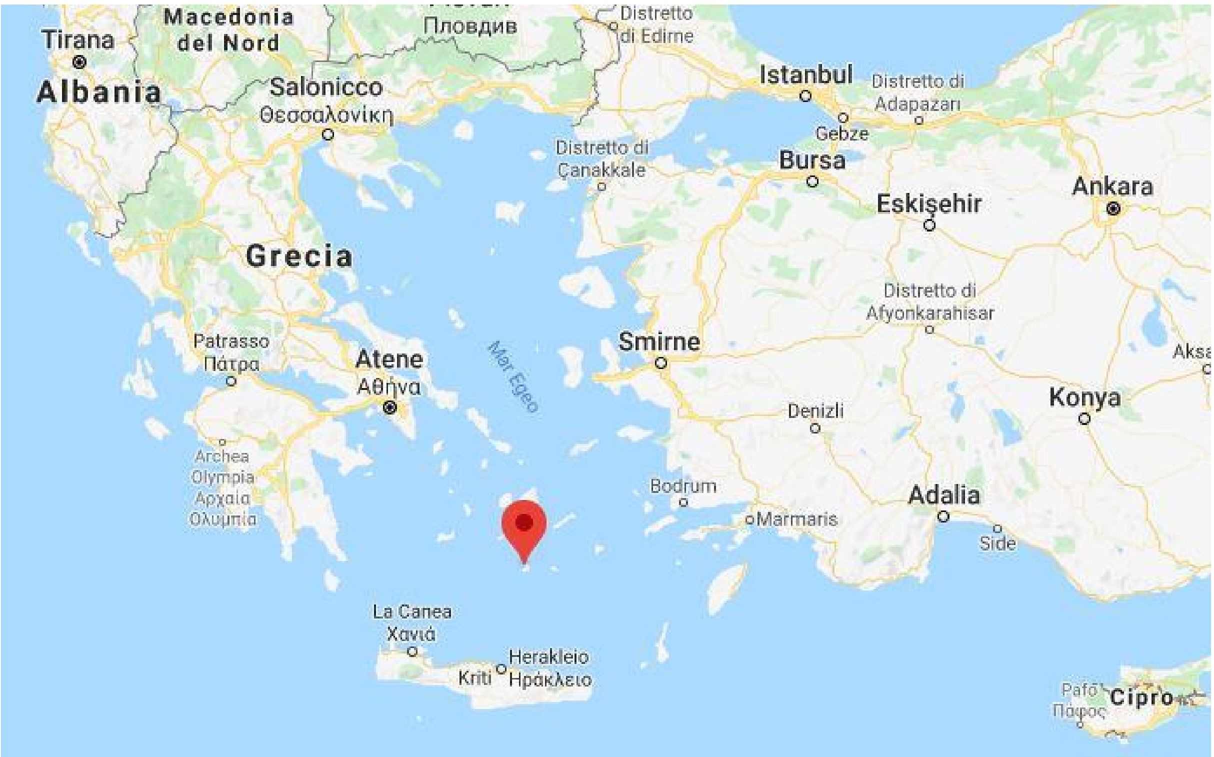

Figure 9: Santorini [3]

Famous for its white cubic-shaped houses, the island attracts an enormous flow of tourists every year, which contributes substantially to the local economy. From an energy point of view, the island is powered by a power plant based on a conventional thermal cycle, which requires 205,67 [€/MWh] [7] for energy production. In August 2012, Santorini was hit by a general blackout that left the island without electricity for several days. Once restored the power, the competent authority (DEDDIE) was forced to use the electricity service only in certain areas of the island at a time to avoid overloads on the line. From this event, it is evident that Santorini needs a technology that allows to minimize the risks of new blackouts. A battery-based or hydrogen-based storage system could be an effective solution to the problem.

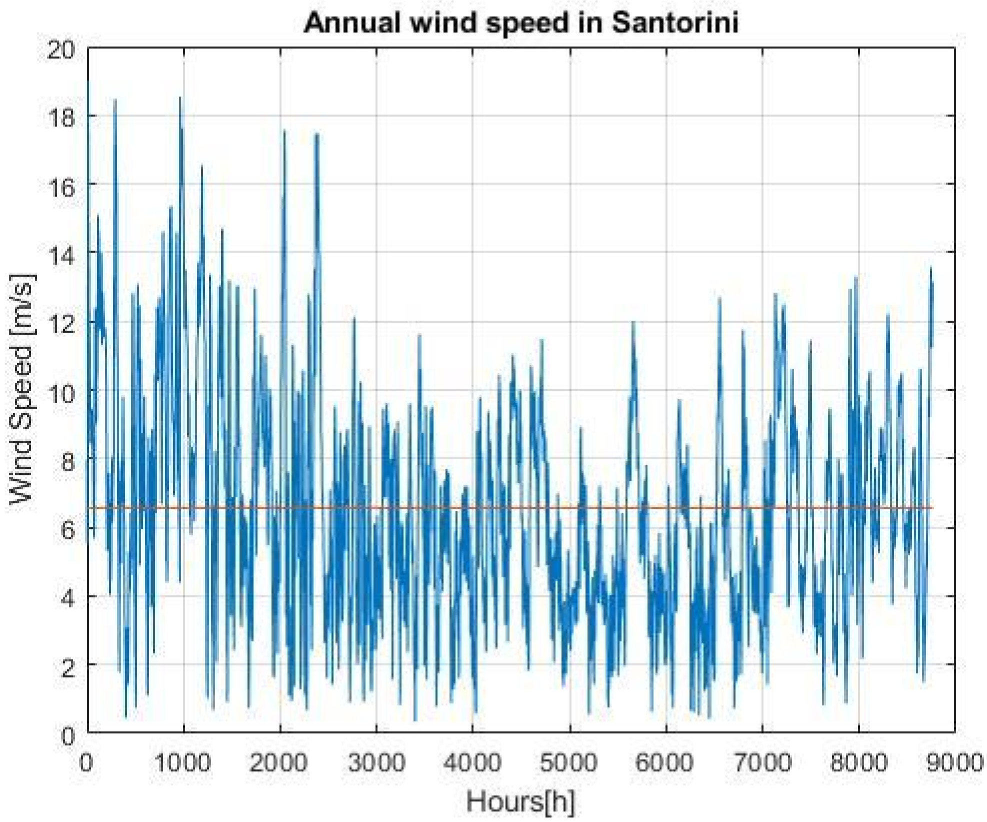

Figure 10: Annual wInd speed at 10m in Santorini

Santorini is an island characterized by strong gusts of wind in the winter that soar the peaks up to over 18 [m/s]. With an average wind speed of 6,3 [m/s], even the third island can be defined as ready to host an energy production system based on wind turbines.

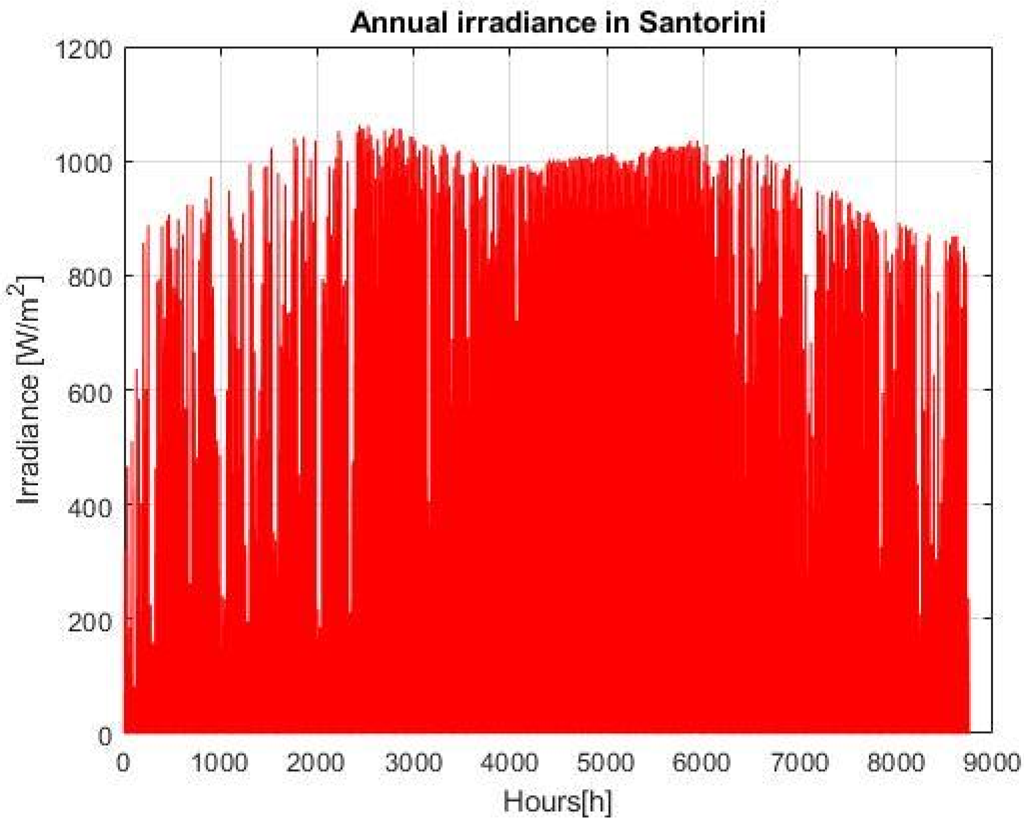

Figure 11: Annual solar irradiance in Santorini

Although the data show excellent annual hourly irradiance values on its territory, for Santorini the morphological aspect of the island should not be overlooked. The numerous reliefs that characterize it could in fact prevent the installation of a photovoltaic system necessary to meet its energy demand.

3.1.4 LESBO

With an extension of 1600 [km^2], Lesbo is one of the largest islands in Greece. Located in the north-eastern part of the Aegean Sea, in the Palagonian zone of the Inner Hellenides [9], the island has a population of 90,643 inhabitants (2001).

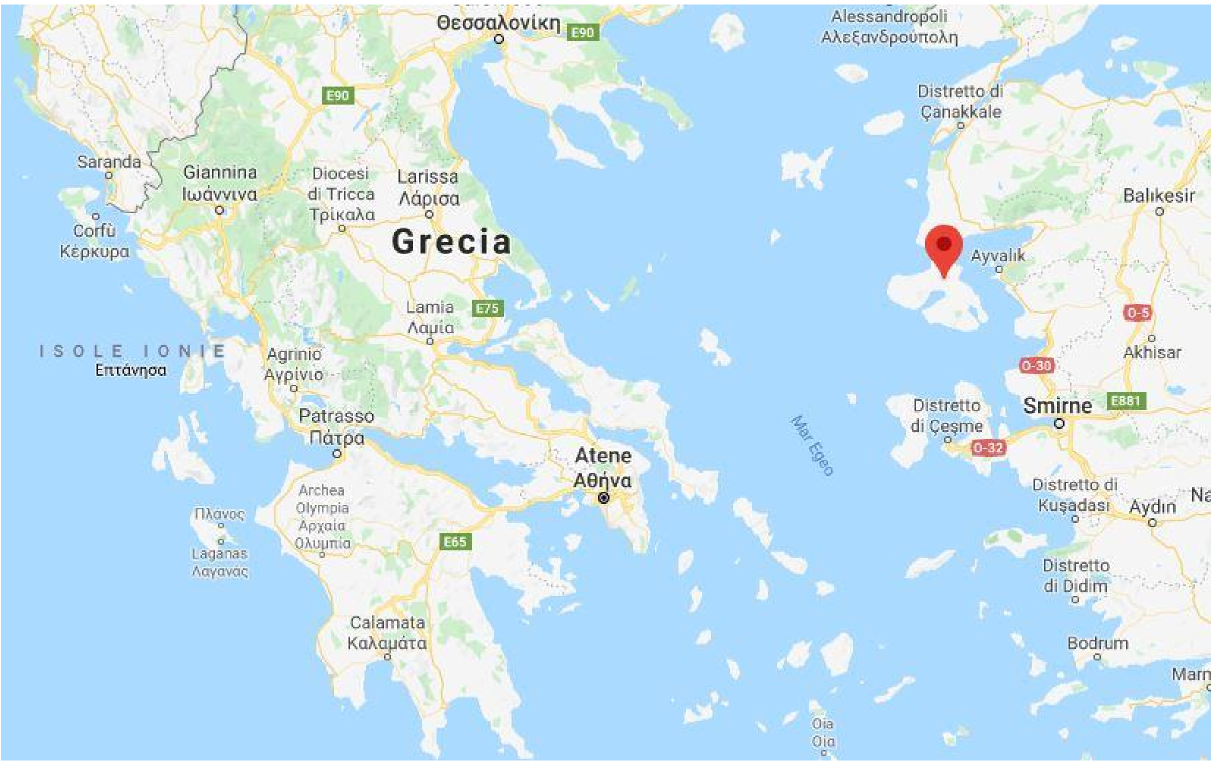

Figure 12: Lesbo [4]

Unlike the other case studies, Lesbo, in addition to the classic activities related to fishing and farming, also hosts various commercial and production activities. Almost half of the population lives in Mytilene, home to the main plants and all the main activities for the development and sustenance of the island. On the island there are several conventional plants for energy generation, which raise the price of electricity to 148,97 [€/MWh] [7]. Part of the electrical load is covered through small plants based on renewable sources. However, these plants belong to private individuals making it difficult to expand the coverage of energy demand from renewable sources in the future. Given the large availability of space on the island, thinking about the installation of a hybrid system based exclusively on photovoltaic panels and wind turbines for electricity generation could be a pioneer for the future development of such systems also on mainland.

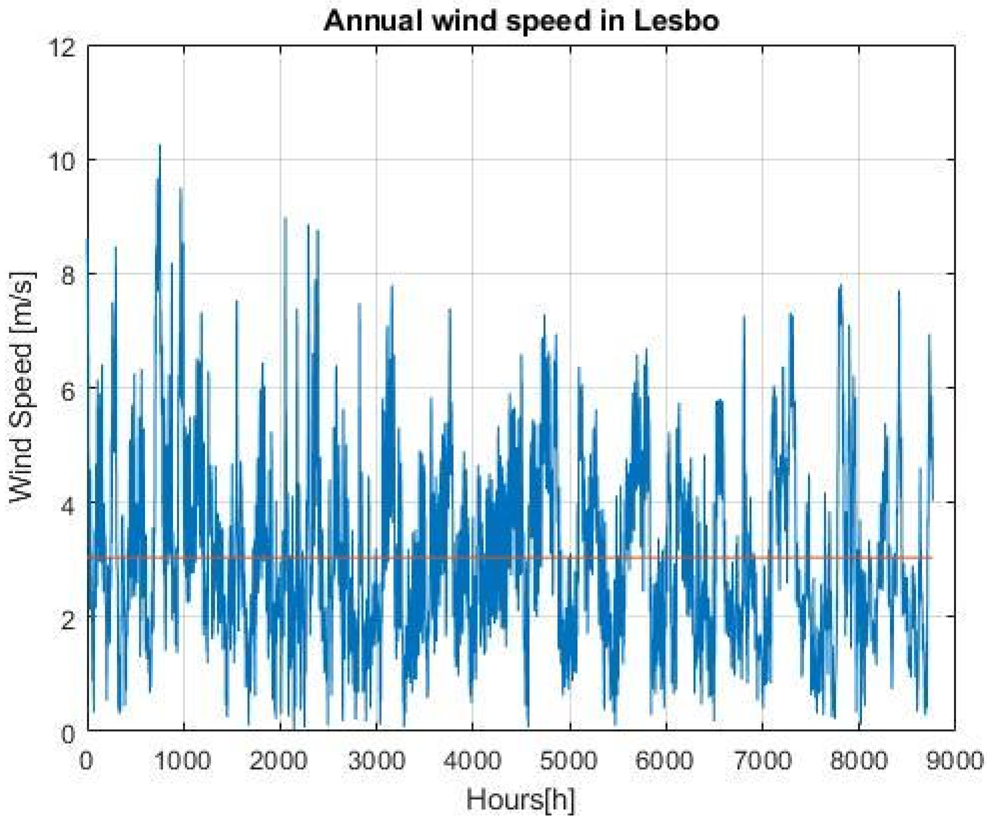

Figure 13: Annual wind speed at 10m in Lesbo

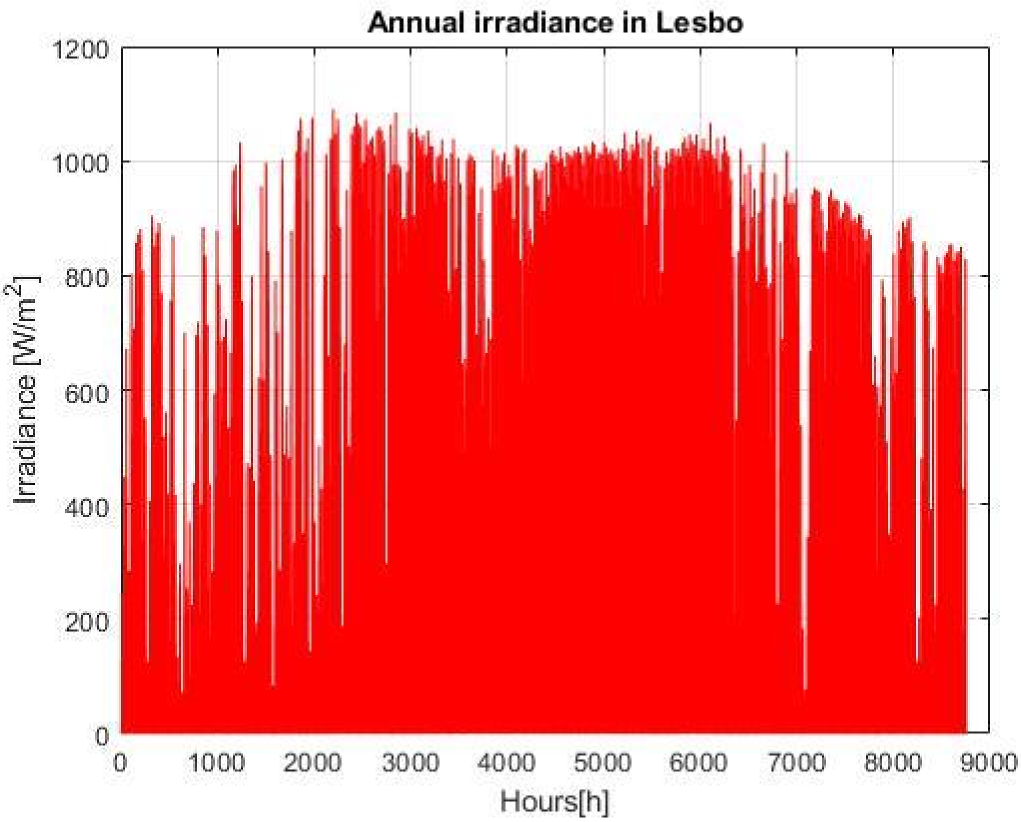

Figure 14: Annual solar irradiance in Lesbo

Unlike the other islands, Lesbos apparently does not have the optimal requirements to activate wind turbines. The average speed of 3 [m/s] is measured at 10 meters from the height of the sea. By reporting the values at the height of the hub of a possible type of wind turbine to be installed, acceptable values are obtained for this island too, which allow the applicability of the technology.

The irradiance is more inconsistent than in the other case studies, but the large availability of land gives the island the possibility of occupying large spaces to make the most of this resource.

3.2 DATA ACQUISITION

The optimization algorithm, which will be presented in section 3, requires three vectors as input, representing the hourly load that the island under analysis requires to satisfy, the hourly power that can be generated by a photovoltaic system and the hourly power that can be generated by a wind farm. The sources of data are described below. In calculating the powers that can be generated by renewable systems, some test peak power values were initially used.

3.2.1 LOAD DEMAND

The load demand that the Greek islands need to cover is mainly of a residential type, since, due to the limited population density that characterizes them and the absence of production plants, the greater consumption is of a domestic type. The islands belonging to the fourth group are an exception, characterized by a type of load including industrial ones, and some islands that see their consumption increase exponentially in the summer months due to the strong tourism to which they are subject.

To be carried out correctly, the analysis requires the annual hourly load profiles of the islands as the input vector. From the official website of IPTO (Independent Power Transmission Operator), which since 2012 has been the owner and operator of the Hellenic Electric Transmission System (HETS) [5], the data relating to the average monthly electrical loads in Greece have been extracted. Data need to be converted from monthly to hourly. To obtain the most truthful load profiles possible, the monthly average values obtained previously were extended to all the hours of the relative months and scaled for the daily load factors that characterize the average Greek per capita consumption. The selected load factors were extracted from a research on the average residential consumption of the city of Athens [10], considering 3 types of load: winter, summer and average annual (Figure 15).

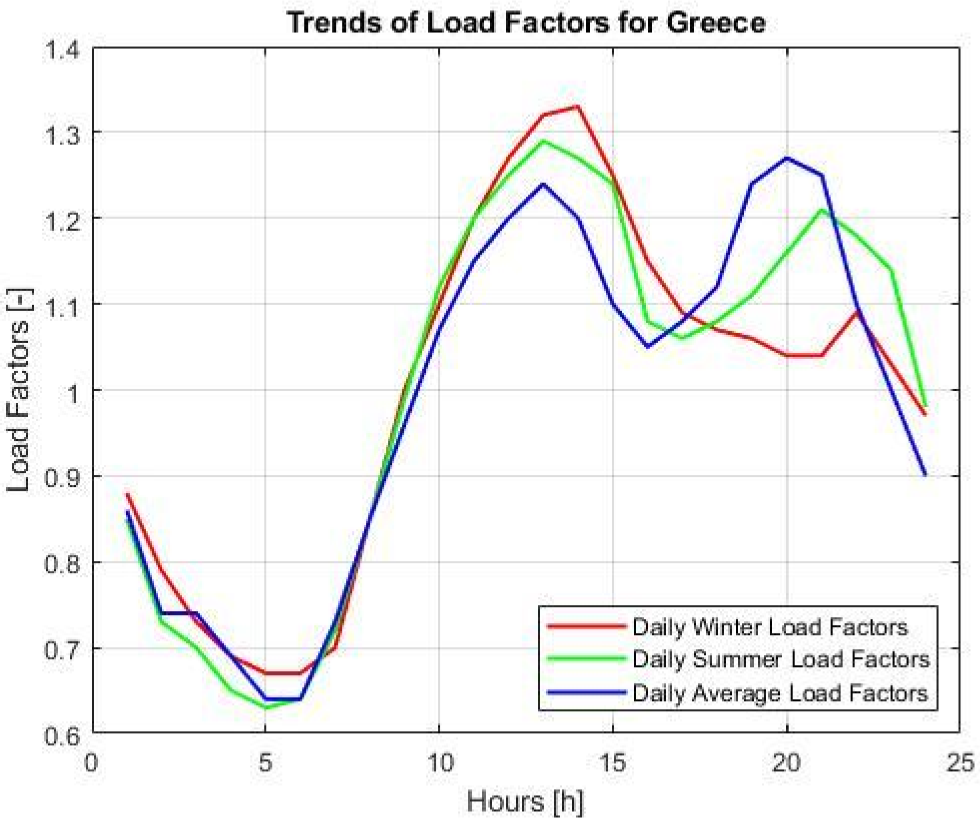

Figure 15: Daily residential load factors of Athens

The data were then scaled according to the relative load factors:

- Winter load factor: from November 21st to March 21st
- Summer load factor: from 21 June to 21 September
- Average annual load factor: from March 22 to June 20 and from September 22 to November 20

The figure below shows the Greek hourly annual load profile. Dividing it by the number of inhabitants of Greece (10768477) and multiplying it by the number of inhabitants of the islands under analysis, the results are obtained.

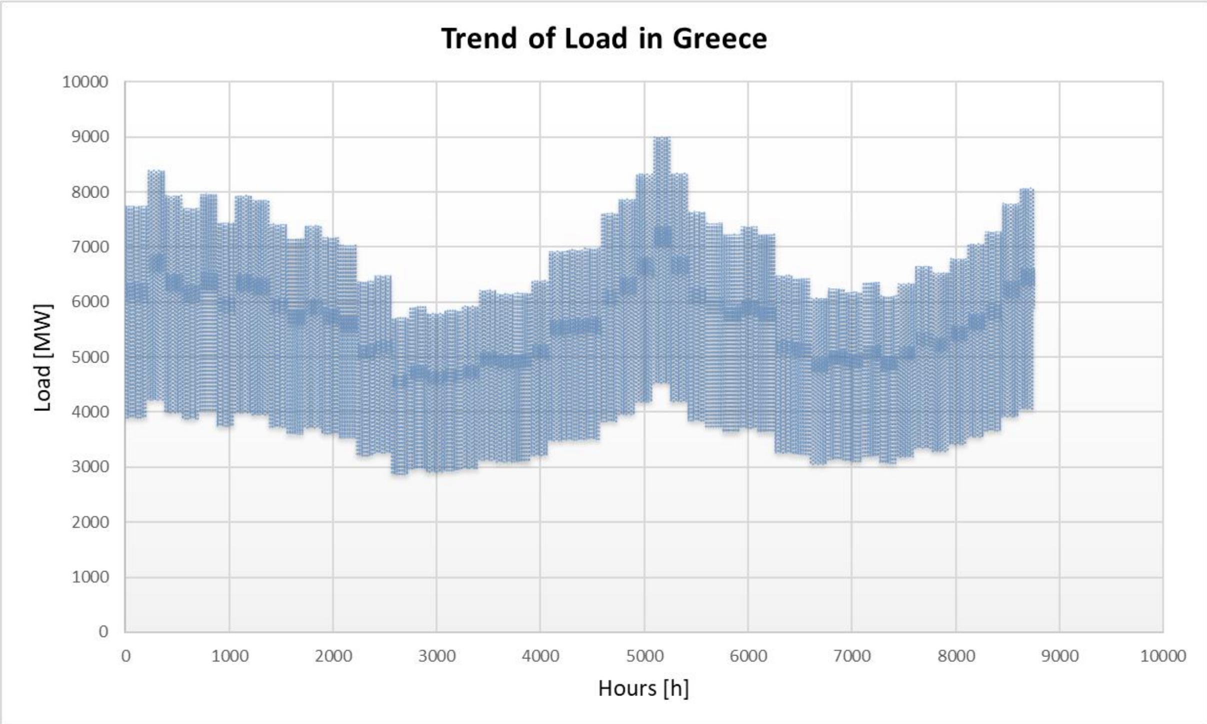

Figure 16: Hourly load demand in Greece

Under the hypothesis of an exclusively residential consumption analysis; the profiles of the 4 analyzed islands will have the same trend as the national one, proportionally scaled according to their number of inhabitants.

3.2.2 SOLAR POTENTIAL

In addition to information relating to solar irradiance, through PVGIS it is possible to obtain information on the power that can be produced by a photovoltaic system. Currently the software is equipped with seven different types of functionality, depending on the user's needs. Also for the potential power that can be produced by the sun, as for the electrical load, the annual hourly values for each island are required. For this reason, the software's "hourly radiation" function was used, which allows to download a time series of hourly solar radiation and/or PV power values [2].

The setup used is shown below.

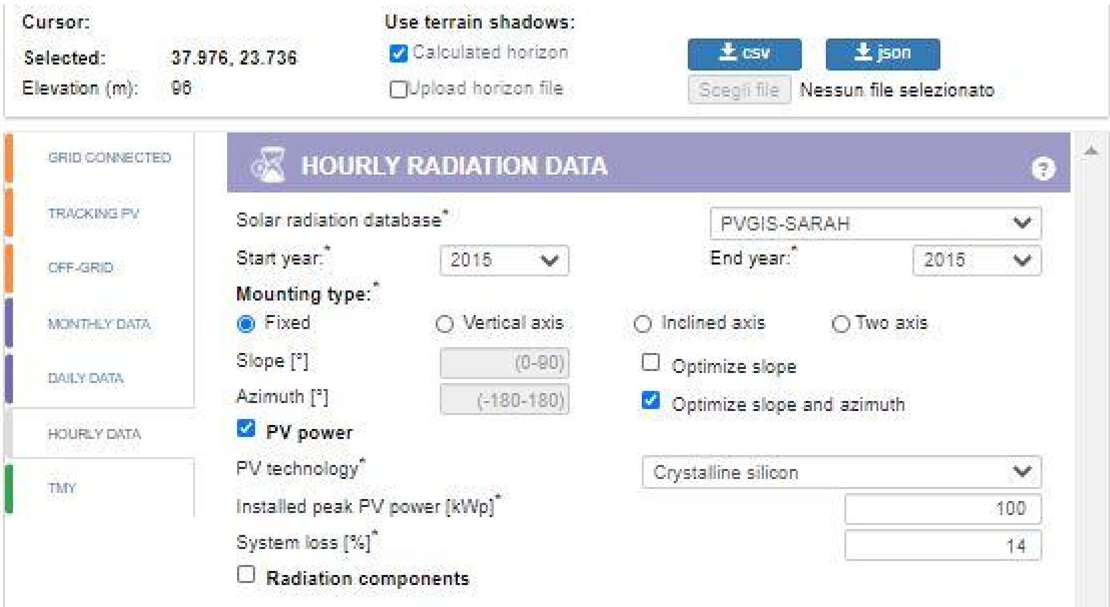

Figure 17: Setup used for PVGIS data acquisition [5]

The selected database was the PVGIS-SARAH. Data are available up to 2016, but since the latter is a leap year, 2015 was chosen as the reference year. The fixed axis type of installation was chosen, by selecting the slope and azimuth optimization option. As a solar panel technology, crystalline silicon was chosen, assuming system losses of 14% and a maximum peak power output of 100 [kW].

3.2.3 WIND POTENTIAL

Starting from the data relating to the wind speed at a height of 10 meters, it is possible to obtain information on the power that can be produced by an onshore wind farm. The speed supplied is measured by anemometers and detectors. These components are generally positioned at a height of 10-15 meters from the ground and have the task of measuring wind direction and intensity. To obtain useful data, the measured speeds need to be reported to the height of the wind turbine hub, as the speed depends on the height and type of terrain.

Given the Z_0 roughness of the ground, the wind speed at the height of the rotor is provided by the following formula:

$$u(h) = \frac{u(h_{ref}) * \ln\left(\frac{h}{z_0}\right)}{\ln\left(\frac{h_{ref}}{z_0}\right)} \qquad (1)$$

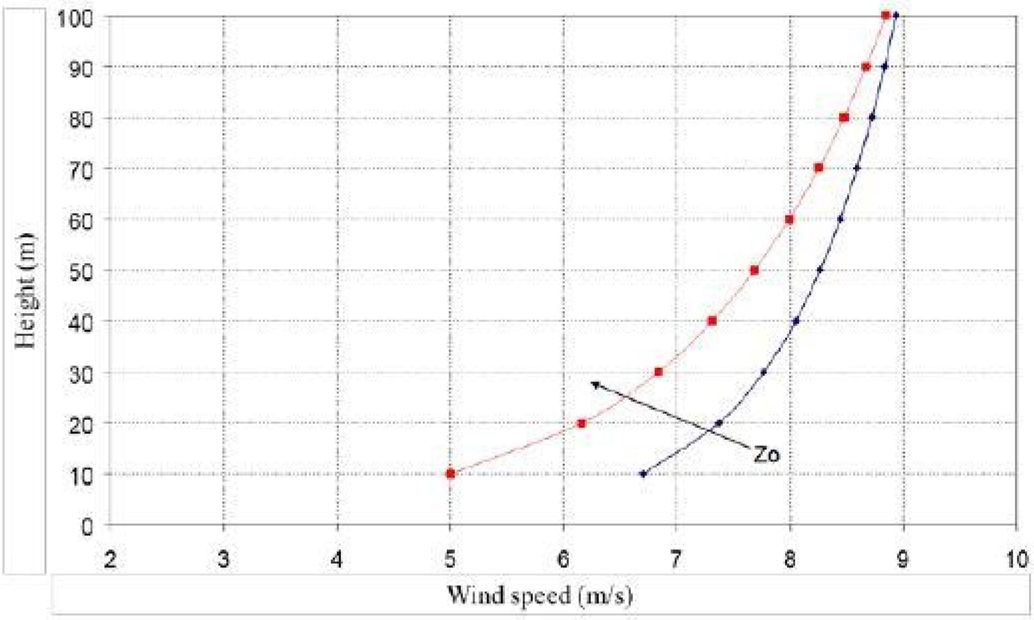

Figure 18: Influence of roughness on wind profile at different altitudes [6]

The figure shows the increasing trend of wind speed with respect to height. The two lines represent two different types of terrain. The lowest roughness values are associated with the blue line, which indicates flat surfaces, such as the sea. The red line instead indicates surfaces characterized by the presence of tall buildings and skyscrapers, which lead to an increase in the roughness value. In general, to be suitable for the construction of a wind farm, a site must have a minimum average wind speed of 5 [m/s] [11]. To proceed in the study of the potential energy that can be produced by the wind in the four islands, two models of wind turbines were selected; respectively:

- Vestas V47 with nominal power of 225 [kW] for Agathonisi [6].
- Siemens SWT-3.6-120-Onshore with nominal power of 3,6 [MW] for the other islands [7].

The following tables provide the main technical characteristics of your turbines and their respective power curves.

Power	Rated Power [kW]	225
	Cut-in wind speed [m/s]	3
	Cut-out wind speed [m/s]	25
Rotor	Diameter [m]	27
	Swept area [m^2]	573
	Number of blades	3
	Power density [W/m^2]	392,7
Tower	Hub height [m]	31,5

Table 5: Data sheet of Vestas V47 wind turbine

Power	Rated Power [kW]	3600
	Cut-in wind speed [m/s]	3
	Cut-out wind speed [m/s]	25
	Rated wind speed [m/s]	12,5
	Survival wind speed [m/s]	70
Rotor	Diameter [m]	120
	Swept area [m^2]	11300
	Number of blades	3
	Power density [W/m^2]	318,6
	Tip speed [m/s]	82
Gearbox	Type	Spuor/Planetary
	Stages	3
	Ratio	1-119
Generator	Type	Asynchronous
	Number	1
	Voltage [V]	690
	Grid frequency [Hz]	50
Tower	Hub height [m]	90
	Type	Steel tube
	Shape	Cylindric

Table 6: Data sheet of Siemens SWT wind turbine

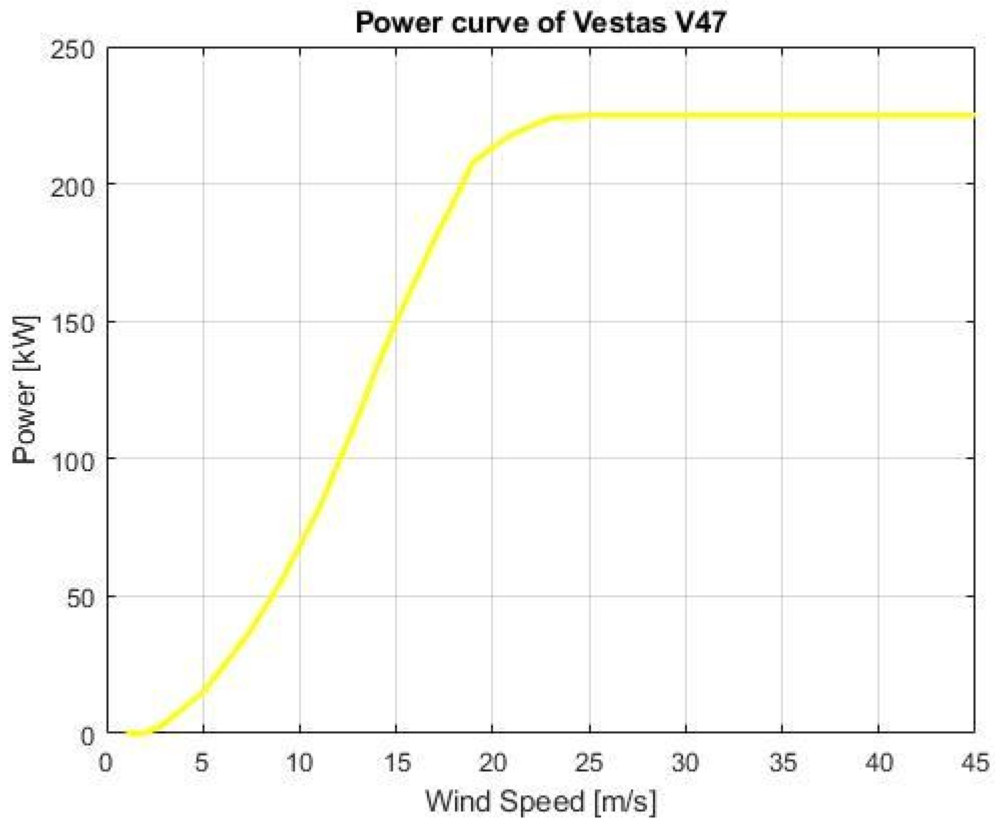

Figure 19: Power curve for Vestas V47 wind turbine

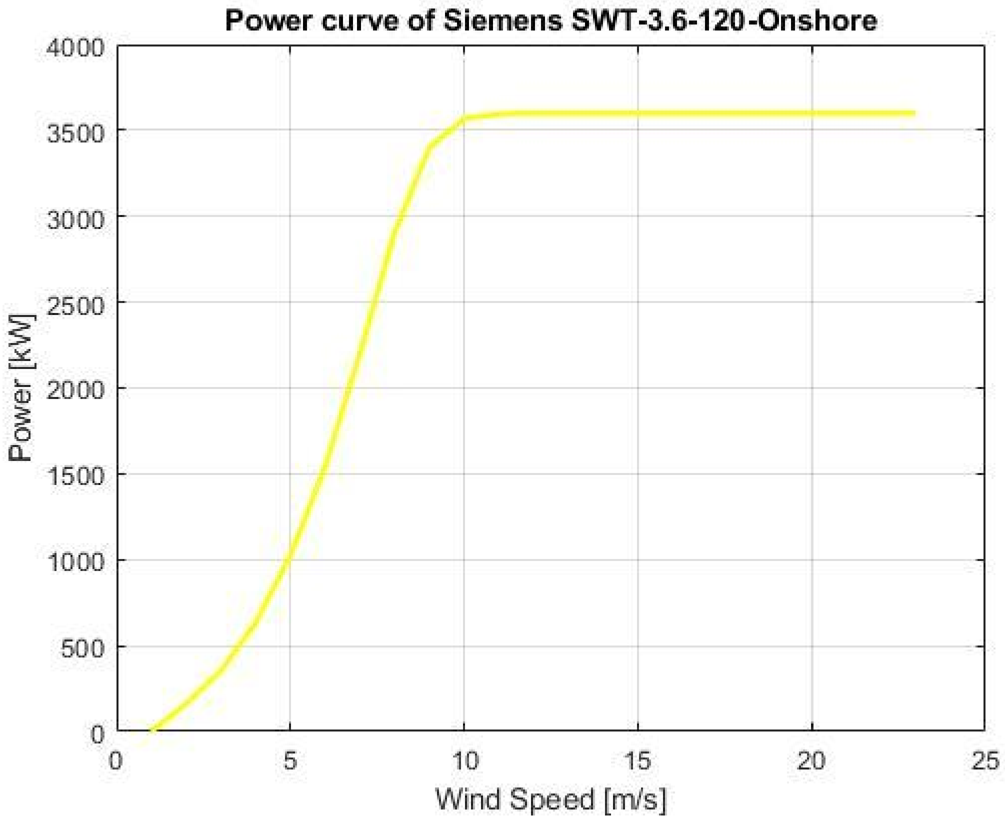

Figure 20: Power curve of Siemens SWT wind turbine

Assuming a roughness value of 0,1 (flat surface) it is possible to obtain the wind speeds at the desired heights.

The power values that can be generated by the wind are obtained by comparing the wind speeds obtained previously with the respective power curve of the turbine used. In the absence of information regarding the evolution of the power function, the two curves have been approximated to two polynomial functions:

$$y = -0{,}0009x^5 + 0{,}075x^4 - 2{,}2782x^3 + 30{,}389x^2 - 151{,}3x + 245{,}49 \quad (2)$$

$$y = -0{,}0217x^5 + 1{,}6811x^4 - 48{,}112x^3 + 604{,}21x^2 - 2861{,}9x + 4444{,}3 \quad (3)$$

Using the necessary boundary conditions, the power values that can be generated by the wind are obtained.

4 OPTIMIZATION MODEL

Within this section, the optimization model implemented to provide the sizes of the plants for the four islands under analysis will be discussed. The general layout of the hybrid system will be illustrated and described below, briefly focusing attention on the various technological elements that compose it. Subsequently, the optimization algorithm and the results that have arisen for each island will be briefly presented, through the analysis of the different configurations explored.

4.1 GENERAL PLANT LAYOUT

The general plant model studied includes two renewable energy generation sources and two storage systems. From the generation of electricity point of view, solar panels and wind turbines have been selected, as they are more efficient and less expensive than other renewable sources currently on the market. These two technologies are able to immediately cover much of the electrical load required by a specific location. However, the solar panels can work at nominal power only at certain times of the day, not neglecting that during the night their production is zero. For wind turbines this problem does not exist, as they depend on the wind speed and therefore under certain conditions, they could work at rated power even continuously. The main problem in this case is the total dependence on the presence of the minimum wind speed. The minimum requirements for their activation may not occur even for long periods, making it impossible to rely exclusively on this technology to generate electricity. The problems presented for these renewable sources are described as "fluctuation problems" and represent the main obstacles for their total affirmation and the future energy transition. The great advances in storage systems such as batteries and hydrogen tanks have marked a turning point towards the definitive use of these resources. The possibility of storing the excess energy produced by solar panels and wind turbines makes it possible to overcome the problems associated with the intermittence of these technologies, allowing the electrical load to be satisfied even when the latter are not active. Two accumulation systems were chosen for the general layout of the analyzed plant. The first is based on batteries, while the second exploits the potential deriving from hydrogen and therefore requires the presence of two other components such as electrolysers and fuel cells.

Figure 21 shows the general layout of the system that will be optimized for each island. The individual components and their operation will be briefly described in the following sections.

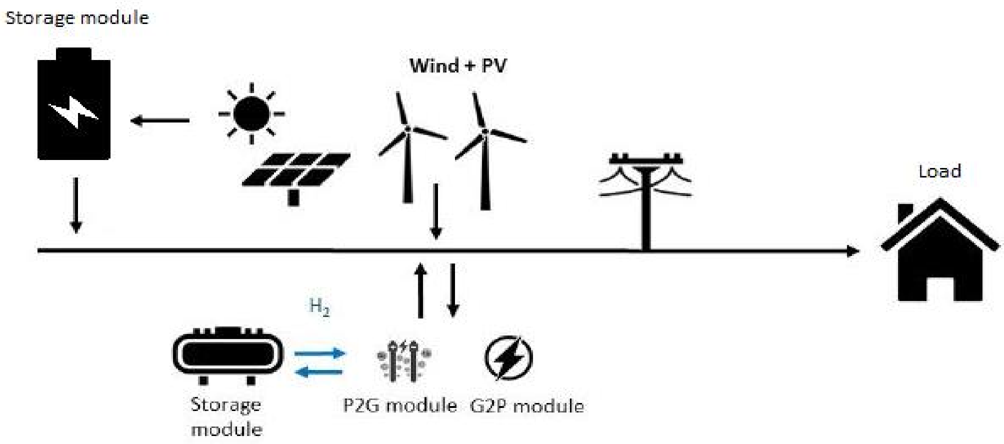

Figure 21: RES solution for electricity generation

4.1.1 PV SYSTEM

A photovoltaic system is a system consisting of small solar cells, made of amorphous, mono or polycrystalline silicon. These cells have chemical contacts, which allow them to be connected in series, formed by silver strips arranged on the surface. The union of several cells in series, generally 36 or 72, forms a photovoltaic module and the photovoltaic system is born from the union of several modules.

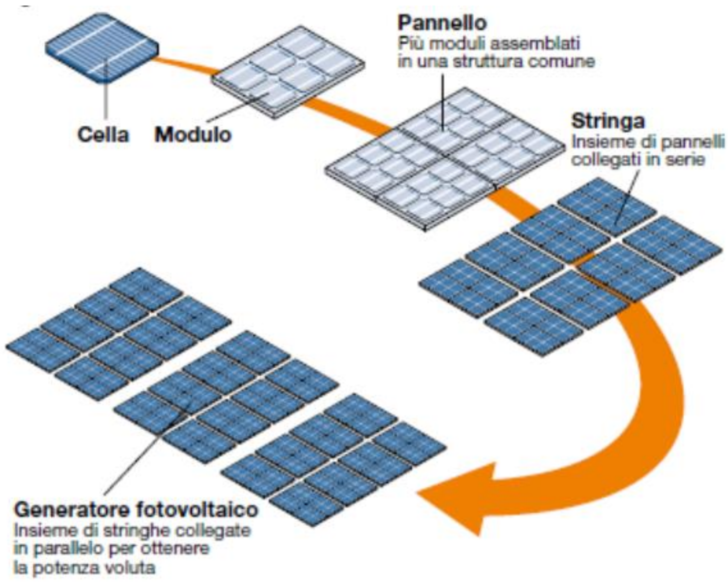

Figure 22: Composition of a photovoltaic system [7]

The electric current supplied by the system is in continuous regime. A residential load such as the one analyzed above, on the other hand, requires an electric current in sinusoidal mode to activate the devices associated with it. To use the various appliances, or for the water heater, or even to turn on the TV, a converter that allows to transform the direct current output from the photovoltaic system into alternating current is needed. It is called inverter [8].

As far as installation and classification are concerned, photovoltaic systems are generally oriented towards south and inclined by 30 °, in order to have the optimal absorption of solar radiation [8]. Depending on the type of installation, however, they can be:

- Autonomous: Not connected to any electricity network and able to produce the energy needed to meet the needs of a home.
- Connected to the grid: They are connected to the electricity grid. In these plants, in the hours in which no energy is produced, this is withdrawn from the local operator's network and vice versa, when the energy produced is sur plus, or is not self-consumed, it accumulates and accounted for it, constituting a credit for the user.
- Stand alone: Installations whose purpose is to supply electricity in areas where there is no local network. This is the case of the Greek islands analyzed, for which a system of this type will be studied and installed in the future.

The general scheme of a Stand-Alone photovoltaic system is shown below.

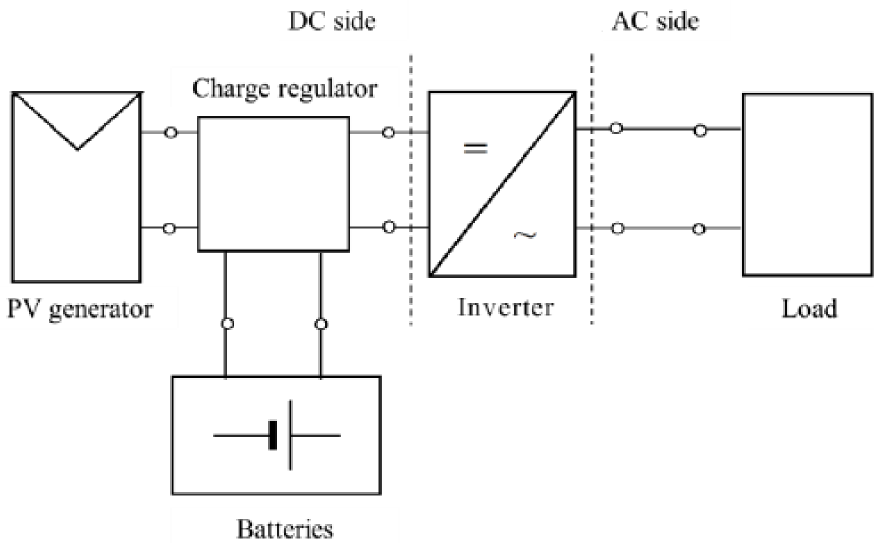

Figure 23: Stand-alone PV plants with batteries to feed AC loads [8]

4.1.2 WIND SYSTEMS

Wind turbines are devices capable of converting wind energy into mechanical rotational energy. Horizontal axis turbines are the most common type. They are placed at a height of even more than 50 meters from the ground and equipped with 2 or 3 blades, generally made of fiberglass and epoxy resin, which can even reach 90 meters in length. The blades are the key to convert wind into mechanical energy and are designed to achieve maximum lift. The converted mechanical power depends on the area covered by the blades: a double length of the blades means quadruple the power produced. The blades are fixed on the hub and joined to the slow shaft (e.g. 30 rpm). A reducer connects the latter to the fast shaft (1500 rpm), which has the task of transmitting the torque produced by the electric generator. The "kinematic chain" is made up of the transmission shafts, the gearbox, the brake and the electric generator, components in a metal case called the "nacelle" [11] (Figure 24).

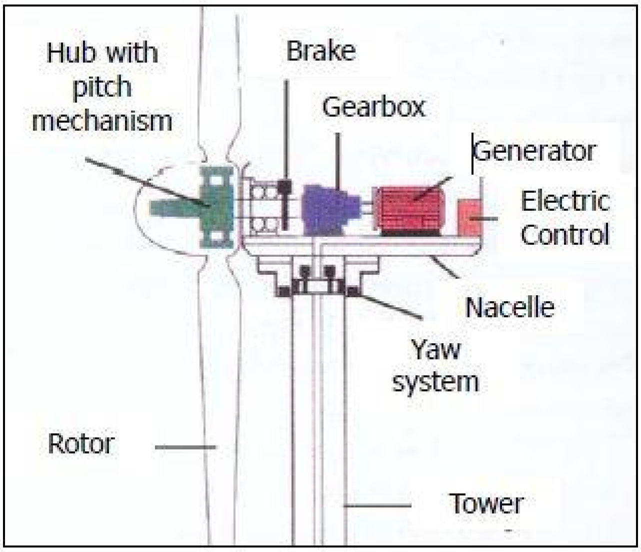

Figure 24: Components of a wind turbine [6]

It is possible to distinguish between systems with constant blade speed and systems with variable speed. The former includes wind turbines equipped with induction or asynchronous generators that allow for a certain variability of the rotor speed with respect to the rotating magnetic field produced (the slip varies from 1% to 10%). Since the wind is a variable energy source, the pitch of the blades needs an adjustment that allows to maintain a constant speed of the blades, as well as to reduce the motor torque of the wind. However, such an adjustment does not allow to maintain the ratio between the peripheral speed of the blades with respect to the constant wind speed, leading to a decrease in performance below the maximum value. In fast turbines with 2 or 3 blades, the optimal ratio of top speed between blade speed and wind speed is between 5 and 10 [11].

Variable speed systems are distinguished using a double bidirectional conversion stage, the first from AC to DC, the second from DC to AC, between the electricity generator and the grid. This makes possible to decouple the electrical generator and the frequency of the grid voltage, ensuring that efficiency is maintained at its maximum value as the wind speed varies [11].

4.1.3 ELECTROLIZERS

Electrolysers are open electro-chemical cells working in reverse operation ($\Delta G>0$). So, they take advantage of the electricity to produce chemicals with high economic and thermodynamic value as the splitting of H_2O into pure H_2 and O_2. For the system designed the source of electrical energy is the one coming from the sur plus produced by the RES system. In the design of the plant is assumed the use of a proton exchange membrane electrolyser (PEMEC). A PEMEC has a low gas permeability, allows to operate at high pressures, has a reduced thickness (R20–300 [mm]) and a high proton conductivity (0.1 ± 0.02 [S*cm^{-1}]). The use of water electrolysis through a PEM to produce pure hydrogen from renewable sources is also one of the best methods from the point of view of sustainability. The high efficiency, compact design, resulting in a small footprint, quick activation response, high current density and low temperature operation (20-80 [°C]) are other advantages as to why to use these devices. The simple balancing of PEM electrolysis plants also makes them attractive for industrial applications. However, using state-of-the-art electrocatalysts for PEM electrolysis such as Pt/Pd makes alkaline water electrolysis very expensive. Therefore, one of the main future goals is to reduce production costs with high efficiency. The constant research towards the improvement of PEM water electrolysis components is increasingly bringing this technology to commercial markets [12].

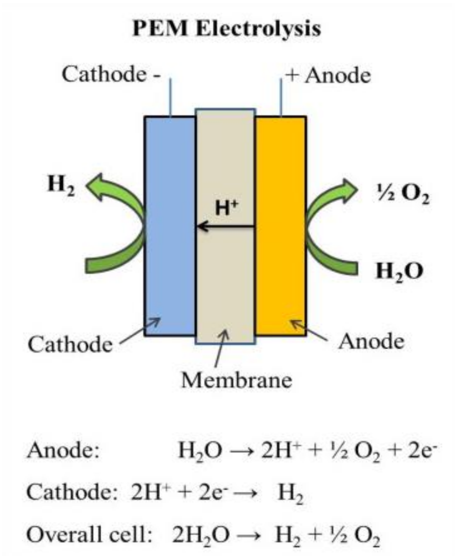

Figure 25: Schematic illustration of a PEM water electrolysis [9]

4.1.4 H_2 STORAGE

H_2 storage is the key process to push the competitiveness and feasibility of all hydrogen-based technologies. The main issue concerning H_2 storage is the low density of hydrogen. In condition of normal temperature and pressure, its density is equal to 0,089 [kg/m^3]. Therefore, hydrogen is characterized by a very high gravimetric energy density (120 [MJ/kg]), but at the same time it has a low volumetric energy density (9,7 [MJ/m^3]). The last term is the most important in the design process of a plant, because volume occupies spaces, which implies high costs. For these reasons, hydrogen can't be stored in normal temperature and pressure condition. This highlights 3 possible solutions:

- Compressed gas storage: H_2 is compressed at 200 or 700 [bars] through a membrane compressor with a respective density equal to 16,4 [kg/m^3] and 57,5 [kg/m^3]. Due to the high cp of hydrogen, the electrical power needed for the compression and therefore the costs will be extremely high. The selection of the vessel's material is an important step in compressed gas storage. H_2 is in fact responsible of the embrittlement process, a phenomenon consistent in the degradation of mechanical properties of the materials constituting the vessel, due to that pressurised H2 can break big grains of metal in much smaller ones.
- Liquid gas storage: The liquefaction of H_2 occurs at 21 Kelvin in normal pressure condition, with a respective density equal to 71 [kg/m^3]. The production of liquid hydrogen occurs through a cryogenic cycle. Once liquified, liquid hydrogen is stored in a vessel constituted of two concentric shells between whom vacuum is generated to avoid conductive and convective losses. Shells are in addiction coated with a low emissivity layer to reduce radiative heat transfer towards internal shell. A relief valve equipped in the vessel has the function of release the evaporated hydrogen day by day.
- Storage in solid structures: H_2 could be adsorbed in a solid structure and stored without chemical bonds through activate carbons or zeolites or absorbed with chemical bonds. In the second case the most used materials are hydrides due to their good density (150 [kg/Nm^3]) and their very low enthalpy of desorption, that makes the future removal of hydrogen very cheap. In the specific, the most widely spread metal hydride is Magnesium Hydride, for which density is 200 [kg/Nm^3].

4.1.5 *FUEL CELLS*

Fuel cells are open electrochemical cells working in galvanic regime (ΔG<0) and consuming the chemical energy contained in the reactants (H_2 and O_2) to produce electrical power. Fuel cells are classified depending on the material composing the electrolyte, which in turn determine the temperature range of operation. Due to their high efficiencies and low emission, Proton Exchange Membrane Fuel Cells (PEMFC) are the technology selected for the design of the power plant. A PEM fuel cell (50-80 [°C]) delivers high power density while providing low weight, cost and volume, making this device a promising candidate as the next generation of power sources for transport, stationary and portable application [13]. From a technical point of view, the main components are the following:

- Cathode: a positively charged electrode, where oxygen is reduced. At the cathode, oxygen reacts with protons (ions H^+) and e^- forming water and producing heat.
- Anode: a negatively charged electrode, where hydrogen is oxidized. At the anode, hydrogen reacts delivering ions H^+ and e^-.
- PEM electrolyte layer: A membrane constitute by a material called NAFION; obtained by adding to the molecule of Teflon a lateral branch which ends with a hydrogen sulphite (HSO_3^-). NAFION allows ions H^+ to pass through it, while it does not to molecules and e^-.
- Bipolar plate: It is responsible of delivering the fuels and removing the products through channels formed on its surface and electrically connect cells in series configuration.
- Gas diffusion layer (GDL): Porous layers electrically conductive, whose function is to transport the fuel/products from the flow channels in the bipolar plates to the reaction site and to electrically connect the electrodes with the external circuit
- Gasket: A material whose function is to prevent gas or fluids leakages.

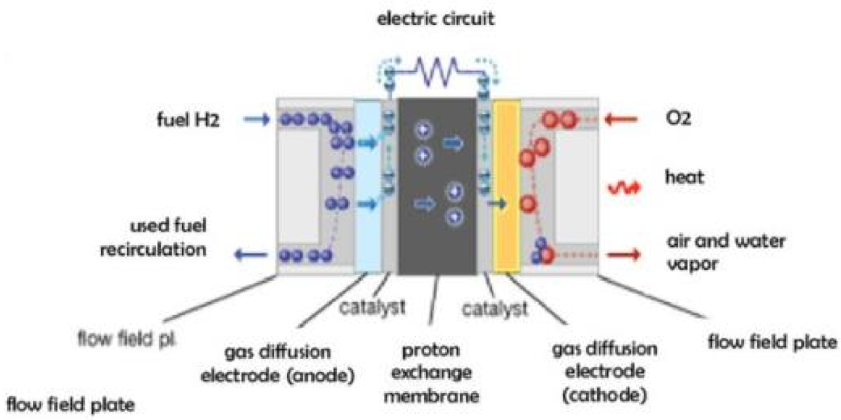

Figure 26: Schematic illustration of a PEM fuel cell [10]

4.1.6 BATTERIES

Batteries are closed electro-chemical cells which can work both in direct and inverse operation. Since they are closed systems, there is no mass exchange with the external environment and materials participating to the electro-chemical reactions (oxidation and reduction) are the same materials that constitute the electrodes.

As introduced, a battery con be operated as a fuel cell, to produce power (direct functioning) or as an electrolyzer, to restore the chemical potential of reactants (inverse functioning). At the market level, Lithium-Ions batteries are the most adopted. From a working point of view, in charged battery in open circuit condition, the Lithium ions intercalated in the anode structure are in equilibrium with the Li-ions in the electrolyte layer. As the circuit get closed, the equilibrium is broken and Li-ions start traveling from anode to cathode, producing the discharge process. First are extracted the atoms neighbouring the electrolyte layer. As the discharge process goes on, all the atoms are extracted, until even those furthest away undergo the intercalation. Contemporary, Li-ions travels across the electrolyte layer and start being intercalated in the cathode structure. First, the occupied sites are those neighbouring the electrolyte layer. Then, the intercalation process goes on until even the furthest sites are occupied. During the discharge process the $\Delta g_{anode\text{-}cathode}$ will decrease until it is no more able to drive battery operation.

In charge configuration, the previous functioning is reversed. As the circuit get closed, the Lithium concentration in the anode structure will vary involving a consequent modification of the $\Delta g_{anode\text{-}cathode}$. The ΔG will grow until it reaches the value associated to the full charge state.

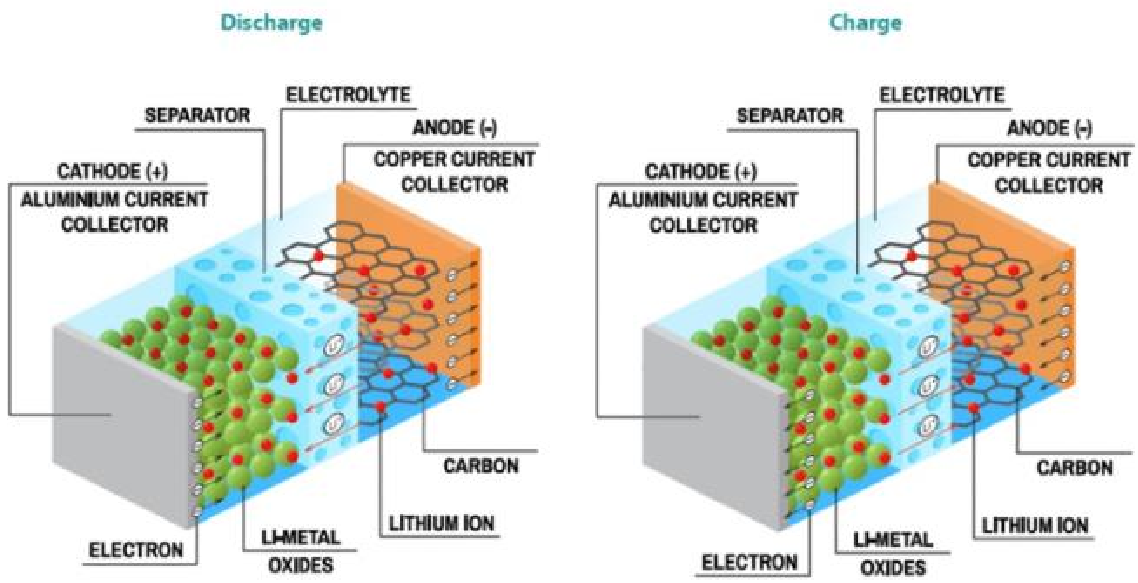

Figure 27: Discharge and charge phases in a Li-ions battery [11]

4.2 PARTICLE SWARM OPTIMIZATION METHOD

PSO is a nature-inspired heuristic optimization method proposed by Kennedy and Eberhart (1995). It is based on two main concepts:

- Simulation of the swarm intelligence and the social behavior observed in animals that group together.
- Evolutionary computation.

The aim of the method is the optimization of a problem by iteratively trying to improve candidate solutions regarding a given measure of quality. A particle is a candidate solution, and improvements are made by moving the particles around in the search space. Position and velocity are influenced by each particle's best-known position, which is also updated by better positions found by other particles in each iteration.

PSO looks for the global minimum solution of a problem by mimicking the social behaviour of flock of birds or school of fishes. How it works to solve numerical optimization problems is listed below [14]:

- The swarm consists of N particles
- Each particle represents a feasible solution $x \in X^n \subseteq R^n$ for the optimization problem, sampling in a multidimensional search space
- At each discrete time step (k^{th} iteration), each particle is located in the search space which fitness is evaluated by the objective function f(x)
- The fitness of each particle represents the quality of its position on the optimization landscape. Here the design vectors (e.g. temperatures for plant design) are quantitatively assessed
- Particles iteratively move and fly over the search space updating their position by using a displacement vector called velocity
- At each time step, the velocity vector of each particle is influenced by randomness, by its own experience and that of its neighbours (intelligent behaviour)
- "Hopefully" the swarm will converge to optimal positions

For each particle x_i at each time step the position x_i^k is updated at x_i^{k+1} by computing a velocity vector v_i^{k+1} using the following equations:

$$v_i^{k+1} = w^k v_i^k + \alpha_1^k \gamma_1 \left(P_i - x_i^k\right) + \alpha_2^k \gamma_2 \left(G_i - x_i^k\right) \qquad (4)$$

$$x_i^{k+1} = x_i^k + v_i^{k+1} \quad (5)$$

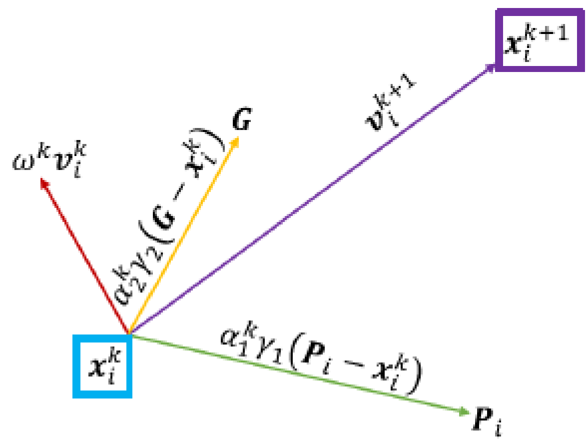

Figure 28: PSO behaviour [12]

The adaptive behaviour is a balance among:

- Cognitive acceleration α_1^k: attraction towards personal best Pi (green line).
- Social acceleration α_2^k :attraction towards global best G (yellow line).
- Inertia weight w^k:momentum of the particle (red line).

PSO uses less resources than traditional optimization algorithms and it can search large spaces of candidate solutions. Also, the method does not use the gradient of the problem being optimized, like classic optimization methods, so this doesn't require the problem be differentiable. However, there is no guarantee that an optimal solution will be found.

The previously described algorithm was used for the sizing and optimal layout of the system to be installed in the four islands. Data relating the electrical load, the power that can be generated by the sun and the power that can be generated by the wind presented in section 2 have been used as input vectors in the Matlab code provided by the PhD student Paolo Marocco, member of the DENERG of the Politecnico di Torino, for each island. The goal is to obtain the sizes of the elements of the plant, imposing a Loss of Power Supply Probability (LPSP) equal to 0%, while minimizing the Levelized Cost of Energy (LCOE). In addition to the optimal solution, hypothetical cases of using only hydrogen or batteries as energy storage systems were subsequently explored.

The following tables shown the boundaries values of each component, while the results obtained are illustrated in the next sections.

Fuel Cell System		
Lower boundary (fraction of the nominal power)	LB_FC [%]	0,1
Upper boundary (fraction of the nominal power)	UB_FC [%]	1
Maximum fuel cell power	P_FC_max [W]	P_FC_nominal*UB_FC*10*3
Minimum fuel cell power	P_FC_min [W]	P_FC_nominal*LB_FC*10*3
Fuel cell efficiency	eta_FC [-]	0,471

Table 7: Boundaries values for Fuel Cells System

Electrolyzer System		
Lower boundary (fraction of the nominal power)	LB_EL [%]	0,1
Upper boundary (fraction of the nominal power)	UB_EL [%]	1
Maximum fuel cell power	P_EL_max [W]	P_EL_nominal*UB_EL*10*3
Minimum fuel cell power	P_EL_min [W]	P_EL_nominal*LB_EL*10*3
Fuel cell efficiency	eta_EL [-]	0,58

Table 8: Boundaries values for Electrolyzers System

Hydrogen Storage		
Minimum operating pressure	p_min [bar]	3
Maximum operating pressure	p_max[bar]	28
Minimun H2 state of charge	SOC_H2_min [%]	p_min/p_max
Maximum H2 state of charge	SOC_H2_max [%]	1
Minimum content of energy in the hydrogen storage	E_ACC_min [kWh]	E_ACC*SOC_H2_min
Maximum content of energy in the hydrogen storage	E_ACC_max [kWh]	E_ACC*SOC_H2_max

Table 9: Boundaries values for Hydrogen Storage System

Battery System		
Maximum battery state of charge	SOC_max [%]	1
Minimun battery state of charge	SOC_min [%]	0,2
Efficiency of battery charging	eta_BT_c [-]	0,92
Efficiency of battery discharging	eta_BT_d [-]	0,92
Minimum content of energy in the battery	E_BT_min [kWh]	E_BT*SOC_min
Maximum content of energy in the battery	E_BT_max [kWh]	E_BT*SOC_max

Table 10: Boundaries values for Batteries Storage System

Converters		
Inverter efficiency	eta_DC_AC [-]	0,955
Electrolyzer converter	eta_conv_EL [-]	1
Fuel cell converter	eta_conv_FC [-]	1
Battery converter	eta_conv_BT [-]	1
PV converter	eta_conv_PV [-]	1
Wind converter	eta_conv_WIND [-]	1

Table 11: Boundaries values for Converters

4.3 AGATHONISI LAYOUTS

The results of the simulations carried out for Agathonisi are shown below.

4.3.1 OPTIMAL SOLUTION

Table 12 report the results of the sizes of the system components in the optimal case.

Optimal case	
LPSP	0
H2 Storage System [kWh]	2900
Battery Storage System [kWh]	0
Electrolyzers System [kW]	105
Fuel Cells System [kW]	130
PV System [kW]	210
Wind Turbines System [kW]	385

Table 12: Agathonisi's optimal layout

The hybrid power generation system includes a total of 595 [kW] of installed power divided into 210 [kW] of photovoltaic panels and 385 [kW] in one or more wind turbines. For the storage system, the optimal solution involves the exclusive use of hydrogen through a 2900 kWh system. A 105 kW electrolysers system and 130 [kW] of a fuel cells system complete the layout of the plant.

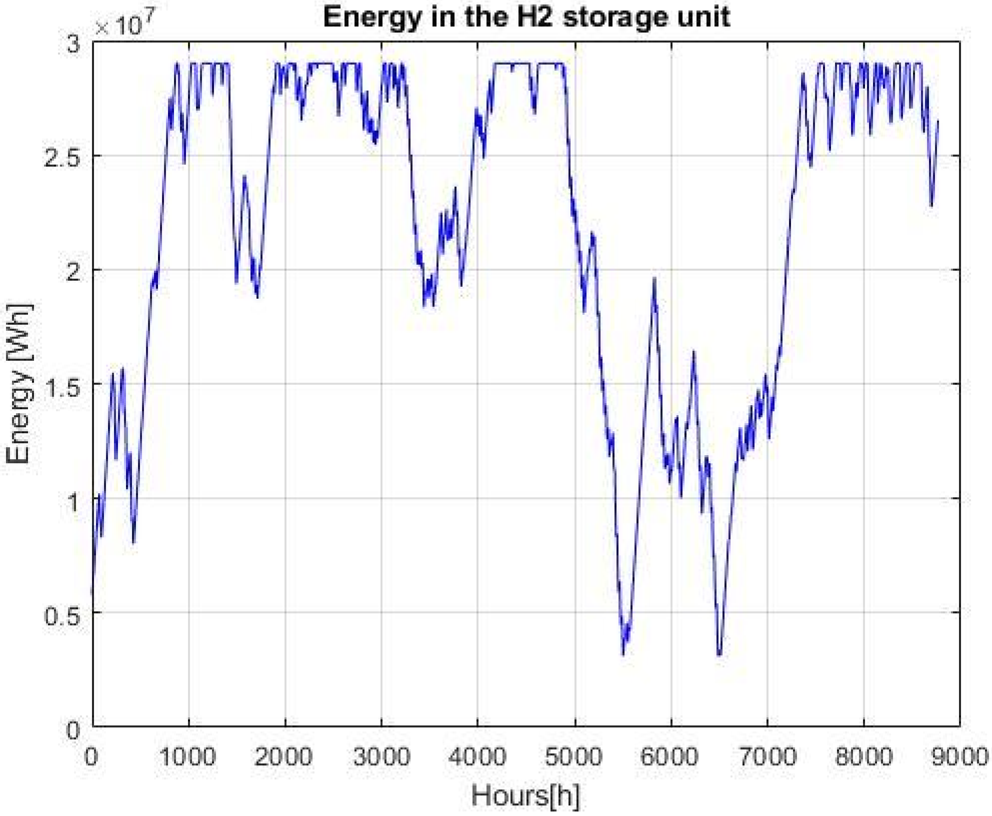

Figure 29: Hourly energy in the H2 storage of Agathonisi

Figure 29 shows the energy trend within the storage system during the year. The hydrogen takes about 1000 hours to reach the maximum level inside the storage, followed by two depressions present between the hours 1400-2000 and between the hours 3200-4200, due to the absence of the minimum wind to activate the wind system. The advent of the summer period leads to an increase in energy demand, due to the influx of tourists, leading, as expected, to a large use of hydrogen between the hours 5000-7200. However, the storage system never reaches zero, proving to be a valid tool for the energy independence of islands not interconnected to the national electricity grid, but above all capable of satisfying their entire energy needs without the use of any fossil source. Overall, the proposed solution allows annual storage of $2{,}54 \cdot 10^8$ [Wh/y], exploiting about 20% of the surplus energy from the PV+WT system.

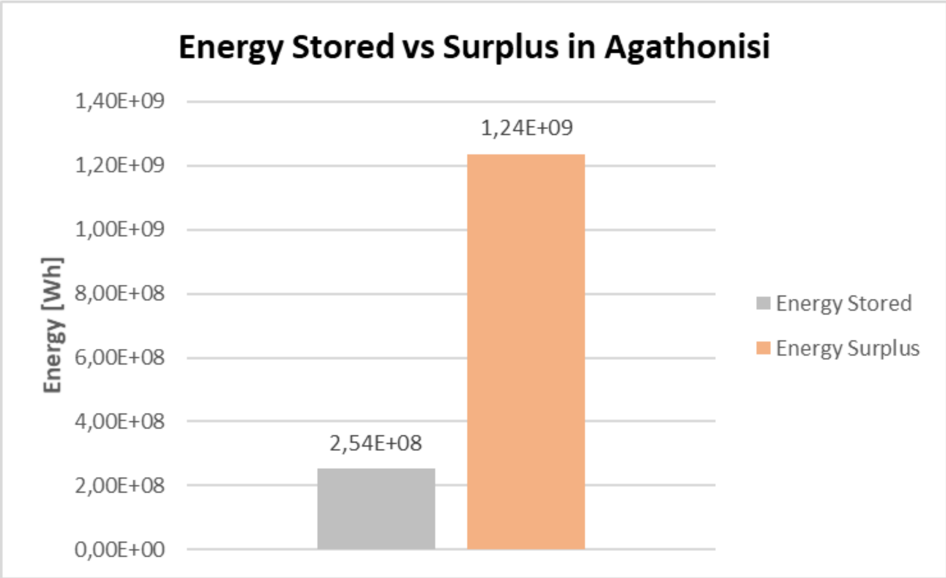

Figure 30: Energy stored vs surplus in Agathonisi

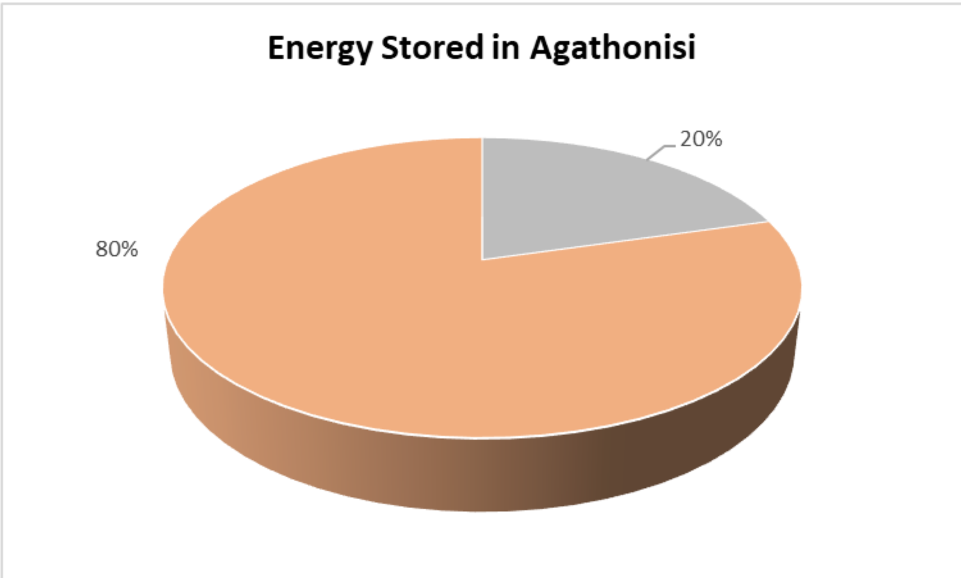

Figure 31: Energy stored in Agathonisi

The activation of the fuel cell system during the year is illustrated in Figure 30.

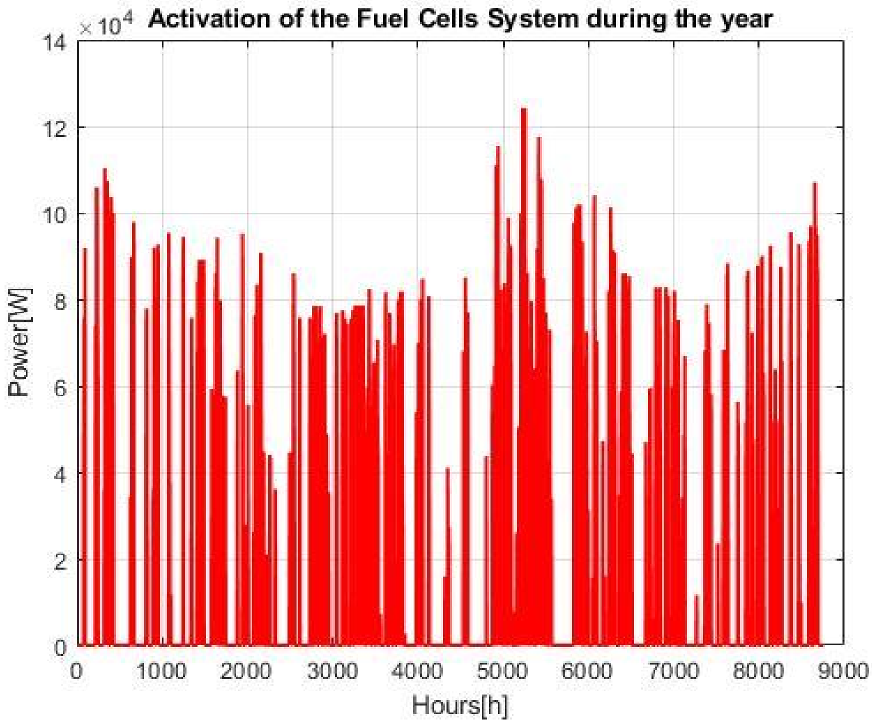

Figure 32: Hourly activation of the fuel cells system in Agathonisi

The system has an intermittent trend, due to the energy consumption by the island directly from the PV systems and wind turbines if they are available. The moments of continuous operation correspond to the periods of lowering of the hydrogen level described above, with the peak corresponding to its minimum level in the storage.

4.3.2 ONLY BATTERIES LAYOUT

Since the optimal solution already presents the use of hydrogen exclusively as a storage system, only the hypothetical scenario of replacing the latter with a battery system was investigated.

Solution with only Batteries	
LPSP	0
H2 Storage System [kWh]	0
Battery Storage System [kWh]	1920
Electrolyzers System [kW]	0
Fuel Cells System[kW]	0
PV System[kW]	985
Wind Turbines System [kW]	110

Table 13: Agathonisi's layout with only batteries

The new configuration has a reduced storage capacity of 1920 [kWh], due to the lack of electrolysers and fuel cells systems, for which conversion efficiencies are around 50%. As a result, the installed power for the hybrid PV panels and wind turbines system is increased to 1095 [kW], almost tripling its value. Since most of this power is distributed over the photovoltaic system (985 [kW]), the island will directly meet its load with it, when available, using the battery system mainly at night, when there will no production from the panels.

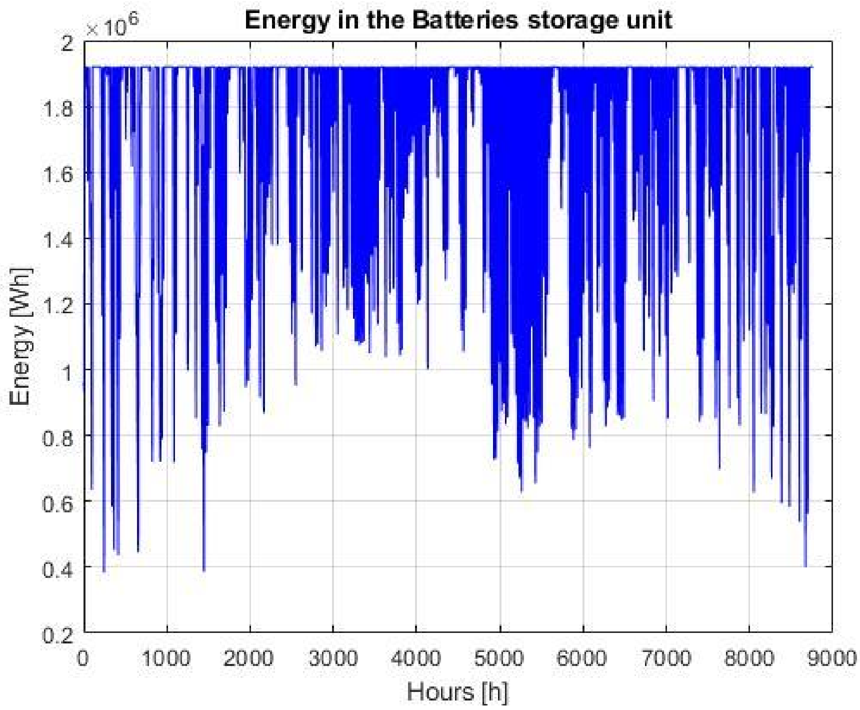

Figure 33: Hourly energy in the batteries-powered storage in Agathonisi

The figure shows the energy trend within the storage. The intermittent trend demonstrates how it is activated mainly at night, with the presence of some areas of continuity corresponding to periods of greater load and moments of low system production due to the absence of wind or covered skies.

4.4 SYMI LAYOUT

Also for the island of Symi, the optimal configuration of the system requires only the use of hydrogen as an energy storage system. The hypothesis of a layout with only the use of batteries was therefore also analyzed in this case study.

4.4.1 OPTIMAL SOLUTION

Proportionally to the increase in the annual and hourly load required by the island, the sizes of the respective system components have also increased.

Optimal case	
LPSP	0
H2 Storage System [kWh]	1200000
Battery Storage System [kWh]	0
Electrolyzers System [kW]	6600
Fuel Cells System[kW]	8000
PV System[kW]	9000
Wind Turbines System [kW]	12000

Table 14: Symi's optimal layout

To cover the annual electrical load, the island requires the installation of a hydrogen storage system with a capacity of 1200 [MWh] coupled to a system of electrolysers and fuel cells of 6,6 [MW] and 8 [MW] respectively. The hybrid system required consists of a 12 [MW] wind farm and a 9 [MW] photovoltaic field, bringing the instantaneous power capacity generated to a total of 21 [MW].

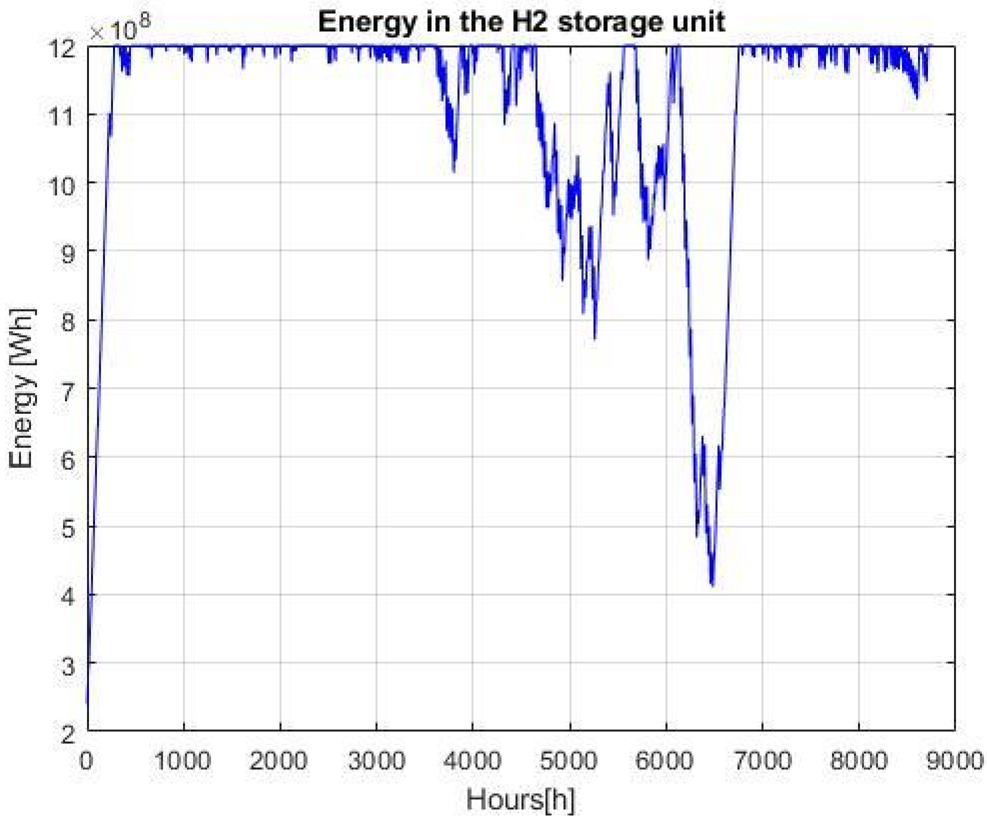

Figure 34: Hourly energy in the H2 storage of Symi

The trend of hydrogen inside the storage shows that the island does not need its use for the first half of the year. After the first charging period, the system shows very slight decreases in the H_2 level before the summer period. The advent of the many tourists inside the island brings the electrical load required to quintuple in the months from June to September, justifying the abrupt decrease in the level of hydrogen inside the vessel. Once the high load period has been exceeded, the storage resumes its charge going back to the project value, obtaining a storage of $9*10^9$ [Wh/h] through the exploitation of 18% of the surplus energy generated by the power system.

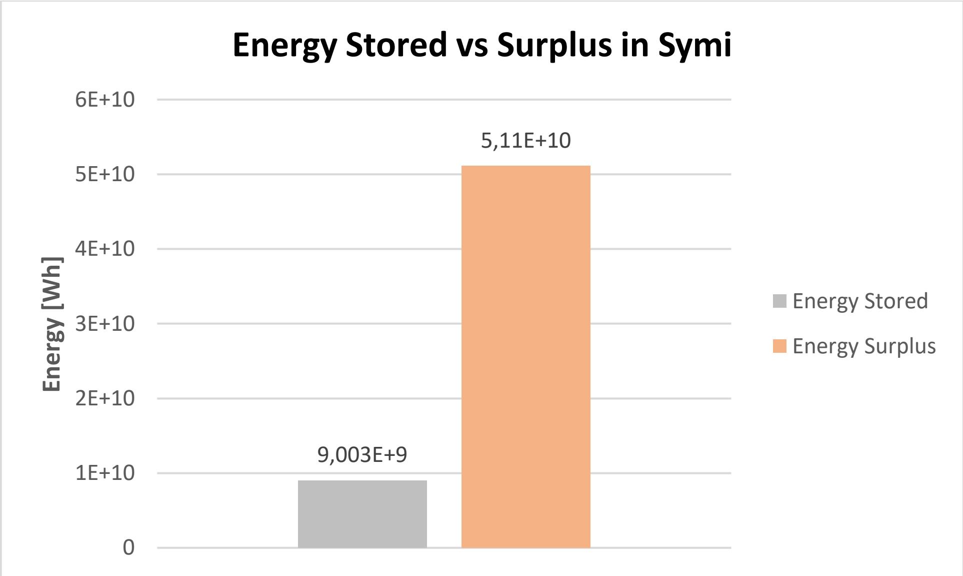

Figure 35: Energy stored vs surplus in Symi

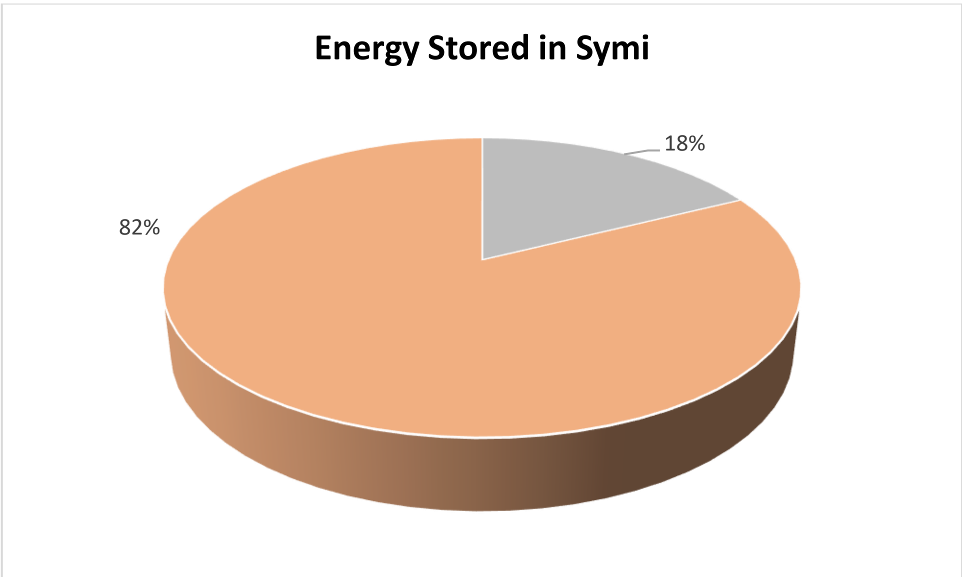

Figure 36: Energy stored in Symi

The need on Symi to exploit hydrogen in the summer is confirmed by the trend in the use of fuel cells, with the peaks of power produced concentrated exclusively in that period.

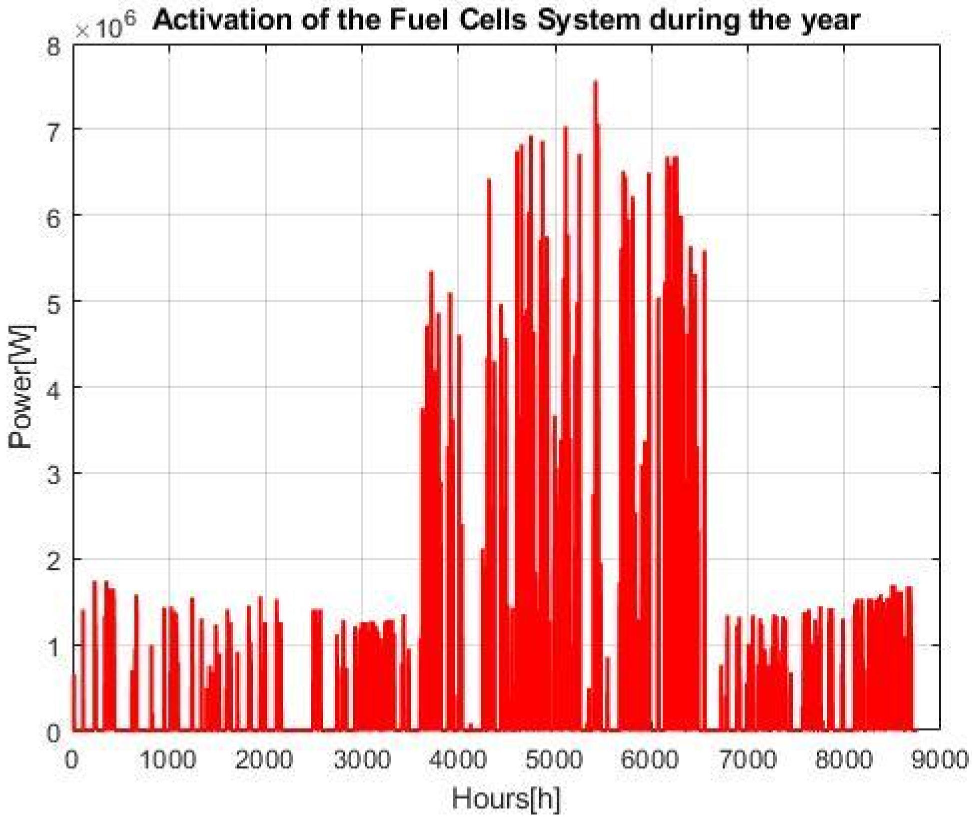

Figure 37: Hourly activation of the fuel cells system in Symi

4.4.2 ONLY BATTERIES LAYOUT

Due to the large capacity required by the storage system for the optimal solution, a possible layout was analyzed that envisages the use of a battery system instead of hydrogen.

Solution with only Batteries	
LPSP	0
H2 Storage System [kWh]	0
Battery Storage System [kWh]	99600
Electrolyzers System [kW]	0
Fuel Cells System[kW]	0
PV System[kW]	28000
Wind Turbines System [kW]	8000

Table 15: Symi's layout with only batteries

The system would seem “leaner” from the point of view of size, passing from 1200 [MWh] to 99,6 [MWh] and therefore decreasing by two orders of magnitude. The installed power for the hybrid system, on the other hand, increases to a total of 36 [MW] divided into 28 [MW] for the photovoltaic field and 8 [MW] for the wind farm. Similarly to the case of Agathonisi, in Symi the increase in the size of the photovoltaic system is linked to its more direct use. Also in this case, therefore, the island will mainly use solar power as a direct energy source, exploiting its sur plus and part of the energy coming from the wind turbines to charge the batteries.

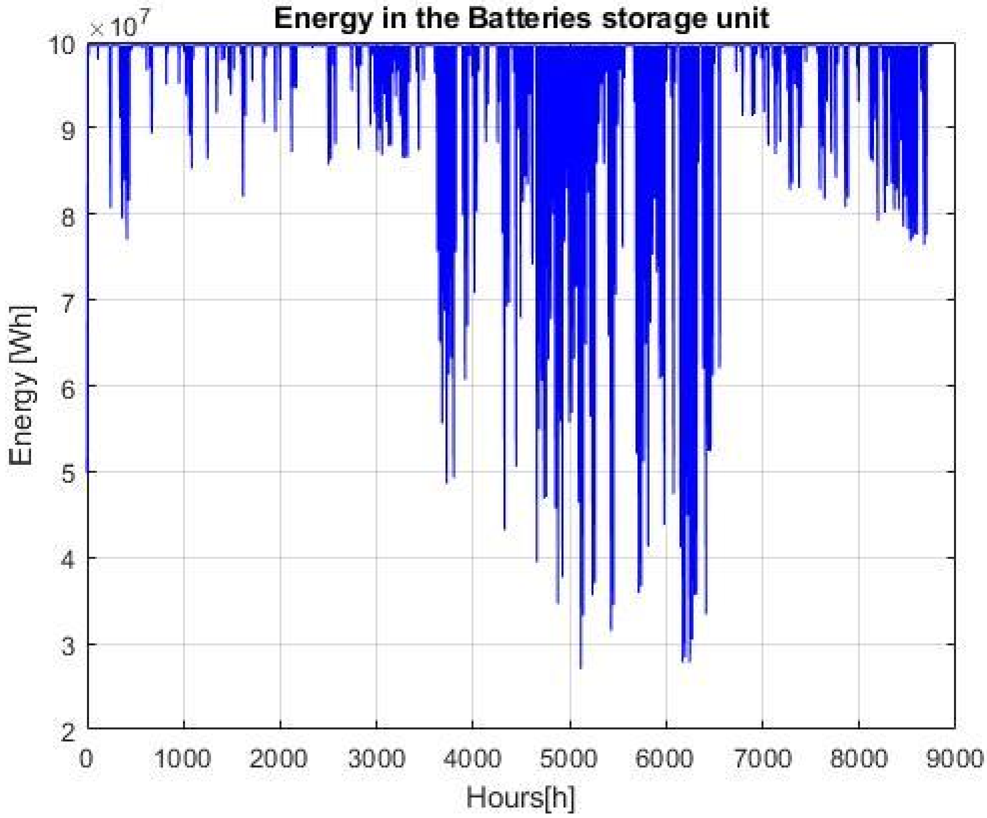

Figure 38: Hourly energy in the batteries-powered storage in Symi

The trend on the hourly use of the storage system confirms what is expressed in the layout of the optimal case, thus being designed to mainly exploit the large load required in the summer period. Both solutions prove to be efficient for achieving the purpose, managing to free the island from a conventional energy production based on diesel generators; a significant result given its non-negligible annual electricity demand.

4.5 SANTORINI LAYOUT

Santorini requires a much higher annual electrical load than the cases analyzed previously. The results obtained by the optimization algorithm are presented below.

4.5.1 OPTIMAL SOLUTION

The optimal solution is based on the same layout obtained for the islands of Agathonisi and Symi, also in this case favoring the use of hydrogen for energy storage.

Optimal case	
LPSP	0
H2 Storage System [kWh]	10635000
Battery Storage System [kWh]	0
Electrolyzers System [kW]	37080
Fuel Cells System[kW]	35870
PV System[kW]	0
Wind Turbines System [kW]	142180

Table 16: Santorini's optimal layout

Unlike the previous cases, Santorini, in the optimal case, does not require a hybrid system to generate electricity, but only a 142,18 [MW] wind farm. For energy storage, a 10,635 [GWh] hydrogen storage system is required coupled with a 37 [MW] electrolyzer system and a 35,85 [MW] fuel cell system. From a technological point of view, it is interesting to note that the lack of use of photovoltaic panels represents a positive aspect. Because of its morphology it would be difficult to install a system of photovoltaic panels that could be able to produce a quantity of power in the order of megawatts. There may also be difficulties for the wind farm, but a solution could be the installation of an offshore system.

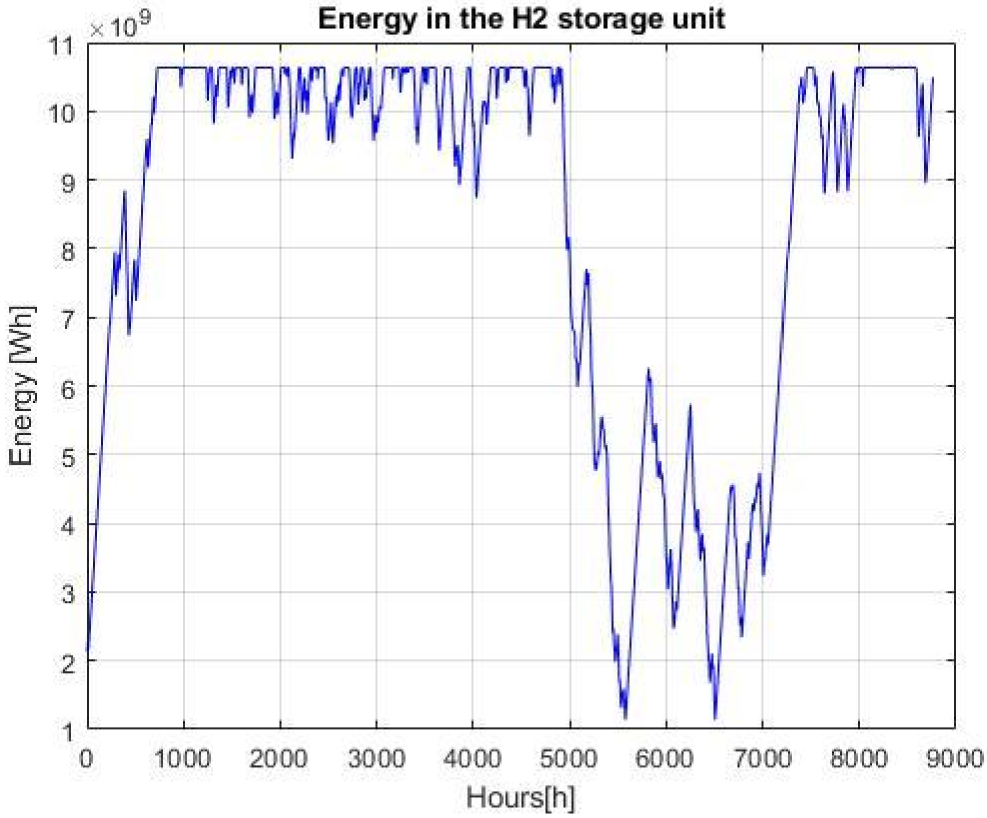

Figure 39: Hourly energy in the H2 storage of Santorini

The trend of energy within the storage reflects a lot the trends seen in the previous islands. Also for Santorini, the period of greatest load is the summer, which leads the island to have an energy consumption comparable to that of islands populated by four times its inhabitants.

The result relating to the annual amount of energy stored inside the hydrogen tank and the relative percentage of energy from the surplus generated by the RES system used is shown below. In the optimal configuration, the system proposed for Santorini would guarantee an annual storage of 7,58*10^{10} [Wh/y] using 13% of the available energy.

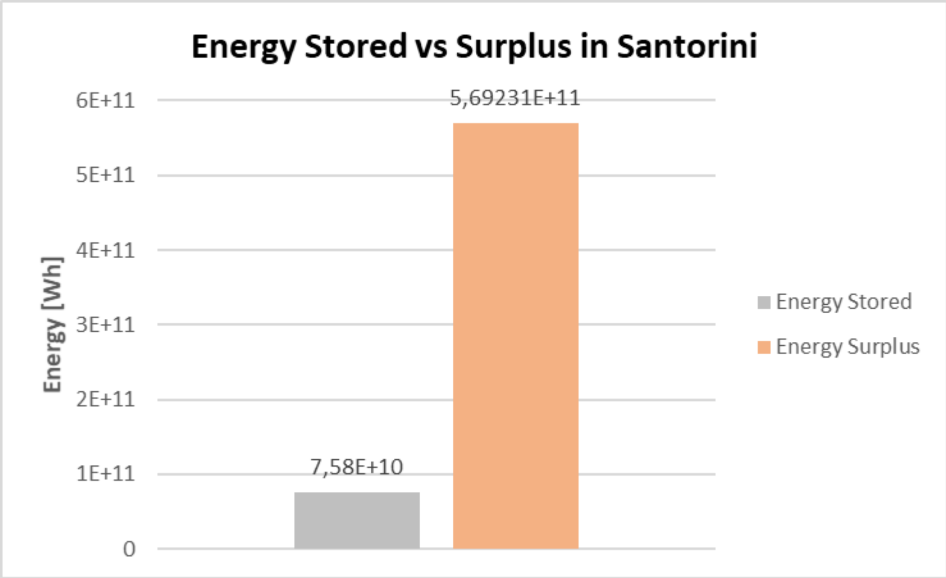

Figure 40: Energy stored vs surplus in Santorini

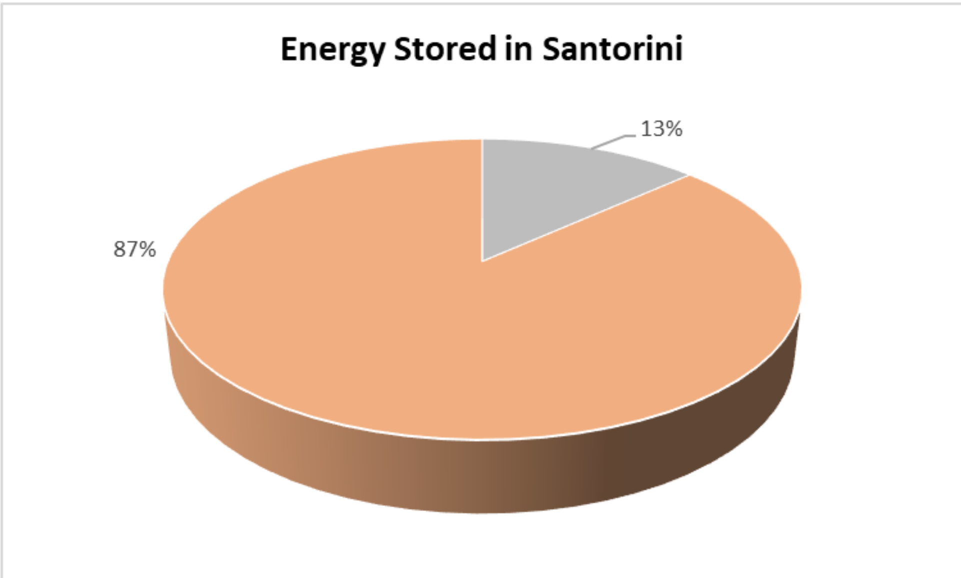

Figure 41: Energy stored in Santorini

The trend of fuel cells may appear not to conform to the hydrogen trend. However, the continuity present in the hours between 4800 and 7200 represents a continuous activation of the system in accordance with the decrease in the value of H_2 within the storage system.

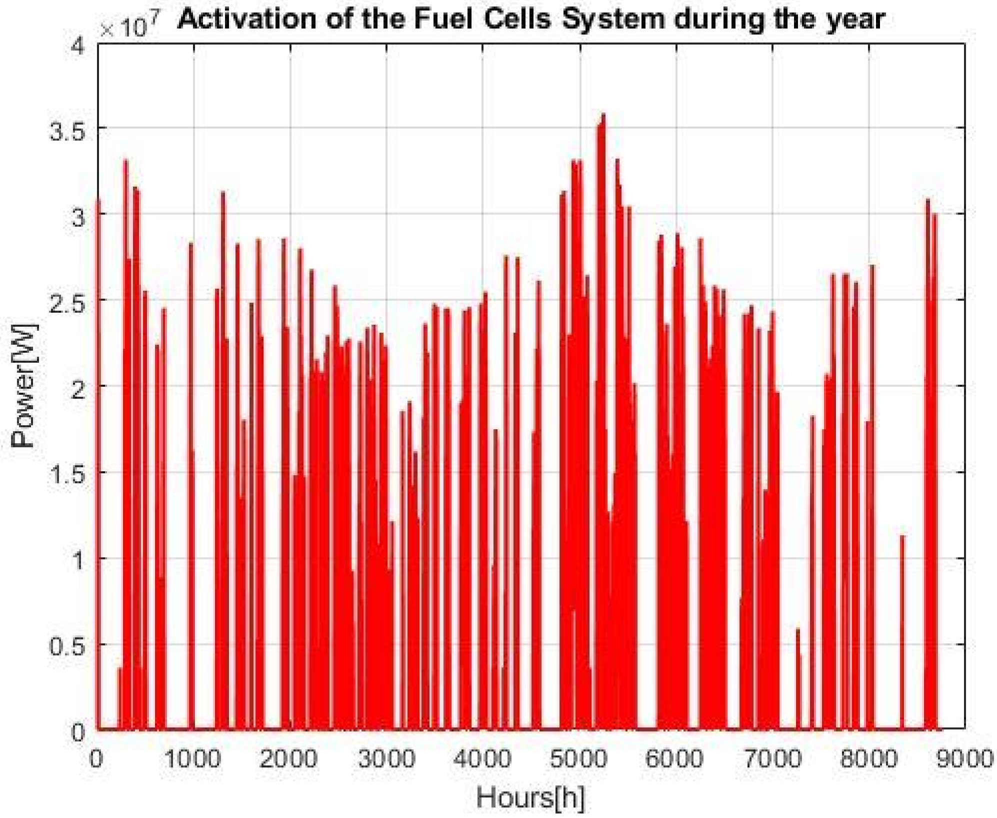

Figure 42: Hourly activation of the fuel cells system in Santorini

4.5.2 ONLY BATTERIES LAYOUT

A system based solely on the use of batteries was investigated to provide an alternative to the use of hydrogen.

Solution with only Batteries	
LPSP	0
H2 Storage System [kWh]	0
Battery Storage System [kWh]	850000
Electrolyzers System [kW]	0
Fuel Cells System[kW]	0
PV System[kW]	265600
Wind Turbines System [kW]	150000

Table 17: Santorini's layout with only batteries

To cover the annual load that the island requires, the battery system to be installed should have a capacity of 850 [MW]. For power generation, the installation of a hybrid system consisting of 265 [MW] of wind turbines and 150 [MW] of photovoltaic panels is required. Unlike the other cases, Santorini has a more regular use of batteries, confined mainly to night hours and proportionate to the required load. The peaks confirm what is expressed, as they are concentrated in the winter and summer period, where load requests increase considerably.

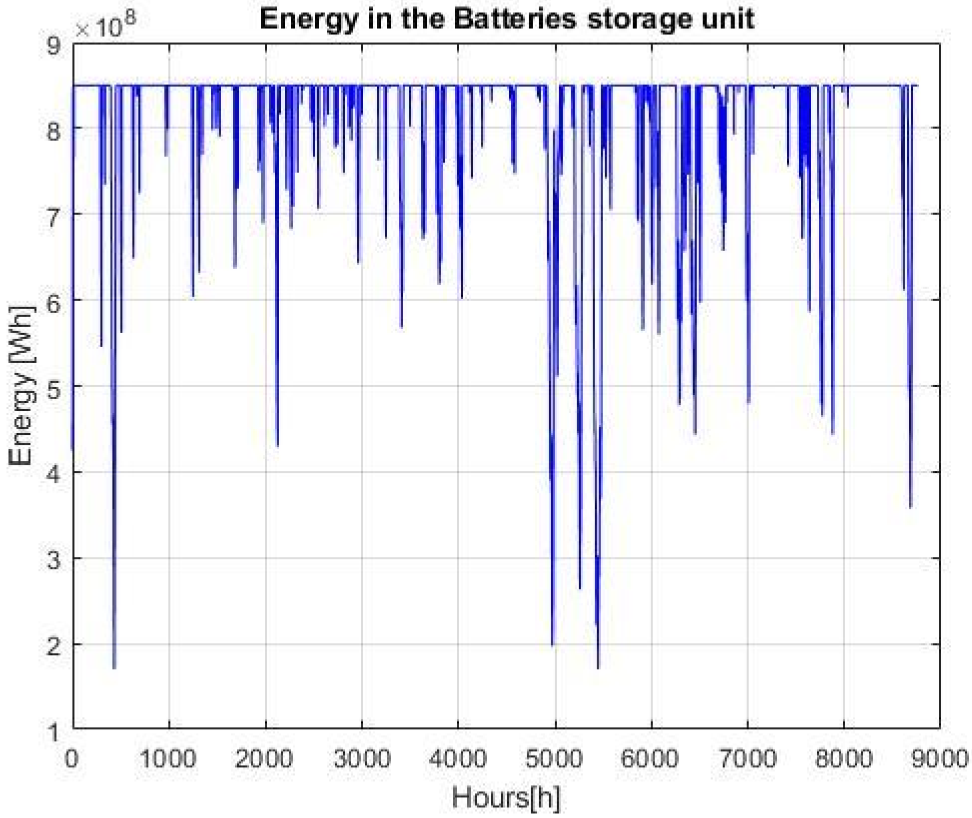

Figure 43: Hourly energy in the batteries-powered storage in Santorini

4.6 LESBO LAYOUT

Differently from all the other islands, three different scenarios were investigated for Lesbos. The results obtained from the optimization algorithm showed the need for a double energy storage system, one using hydrogen and the other consisting of batteries. Two alternative scenarios were therefore analyzed that envisage the use of only one of the two technologies as a storage system.

4.6.1 OPTIMAL SOLUTION

Optimal case	
LPSP	0
H2 Storage System [kWh]	34000000
Battery Storage System [kWh]	18515
Electrolyzers System [kW]	394300
Fuel Cells System[kW]	55400
PV System[kW]	0
Wind Turbines System [kW]	830000

Table 18: Lesbo's optimal layout

The optimal solution involves the exclusive use of an 830 [MW] wind farm to meet the immediate load required by the island. For energy storage, the island requires the installation of a hybrid storage system consisting of 18,5 [MWh] of batteries and 3,4 [GWh] of hydrogen. The layout of the plant is completed by a system of electrolyzers of 394,3 [MW] and 55,4 [MW] of fuel cells.

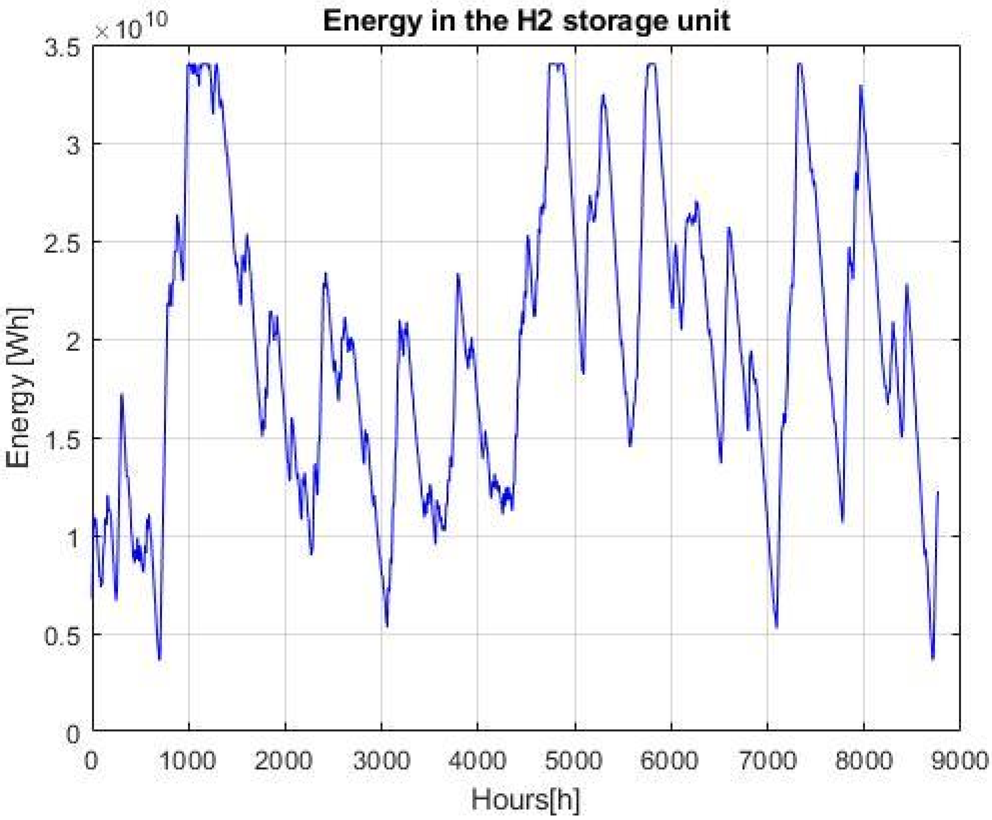

Figure 44: Hourly energy in the H2 storage of Lesbo

The trend of hydrogen inside the storage is in contrast with the previously results. It undergoes discharges and charges throughout the year, meaning constant use of the system, as the contribution of photovoltaic panels and wind turbines alone is not sufficient to meet the demand for electricity. The exploitation of surplus energy also presents anomalies. Unlike the other cases, Lesvos in fact exploits about 42% of the surplus energy coming from the PV + WT system, where a very low percentage belongs to the contribution coming from the batteries (0.5%), while the remaining 41,7% belongs to the hydrogen system. The total energy stored by the solution in one year is thus equal to $3{,}34 \cdot 10^{11}$ [Wh/y].

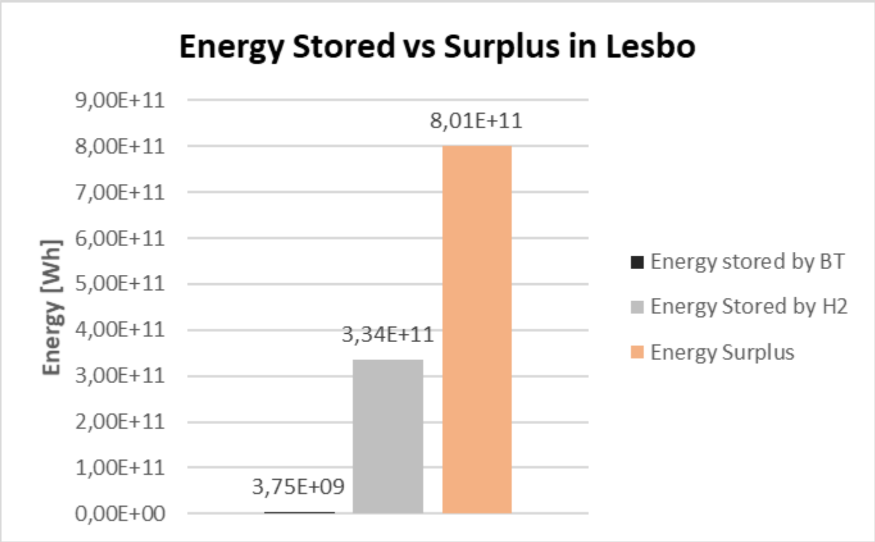

Figure 45: Energy stored vs surplus in Lesbo

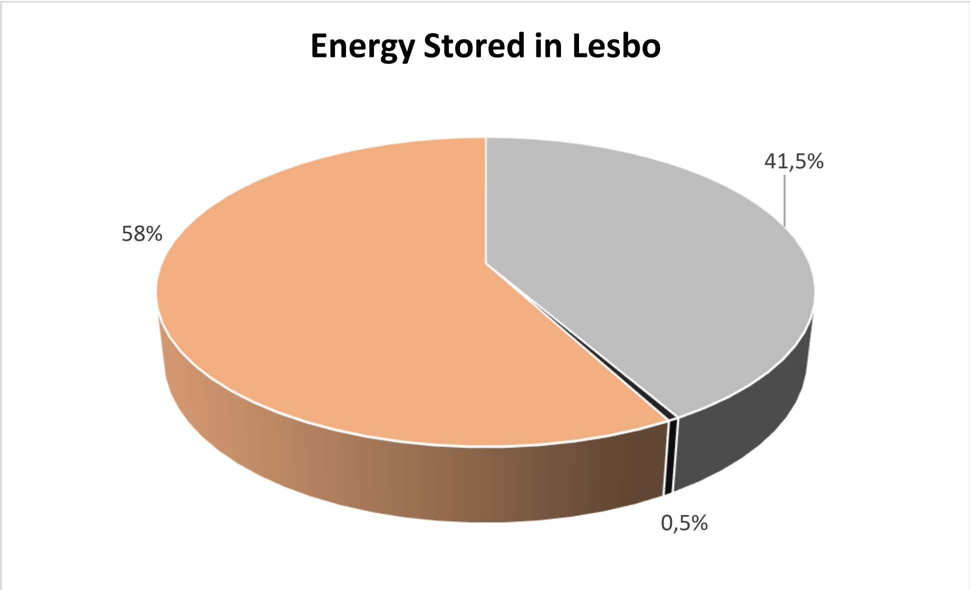

Figure 46: Energy stored in Lesbo

The trend of the power produced by the fuel cells (Figure 49) confirms the previous consideration. The presence of numerous areas of continuity shows that the system is activated constantly, constituting a fundamental element for the hourly electricity supply.

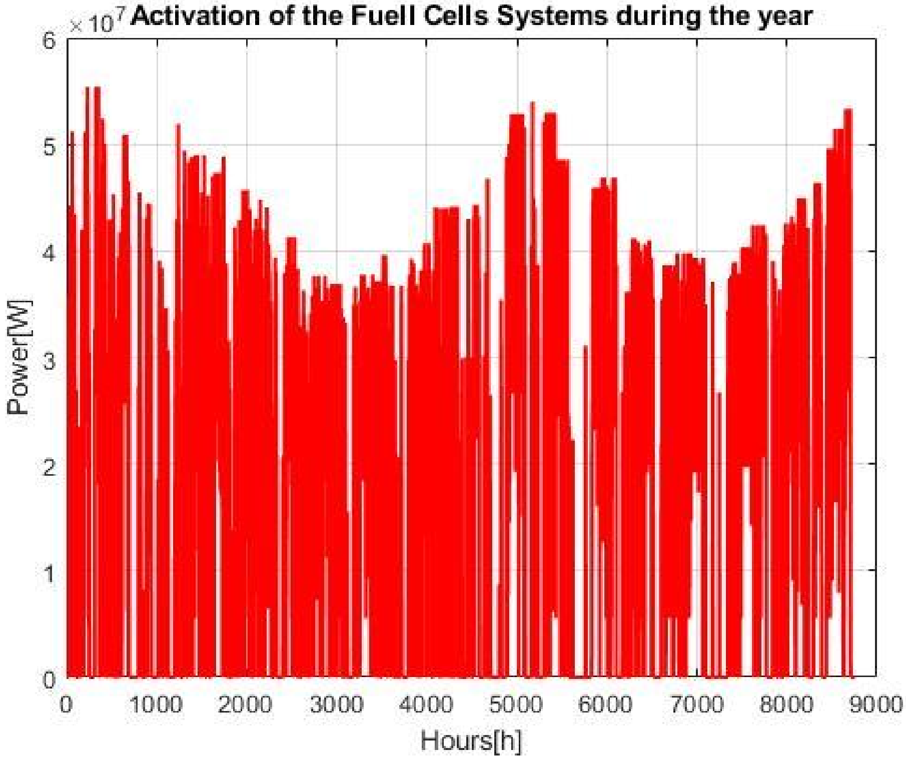

Figure 47: Hourly activation of the fuel cells system in Lesbo

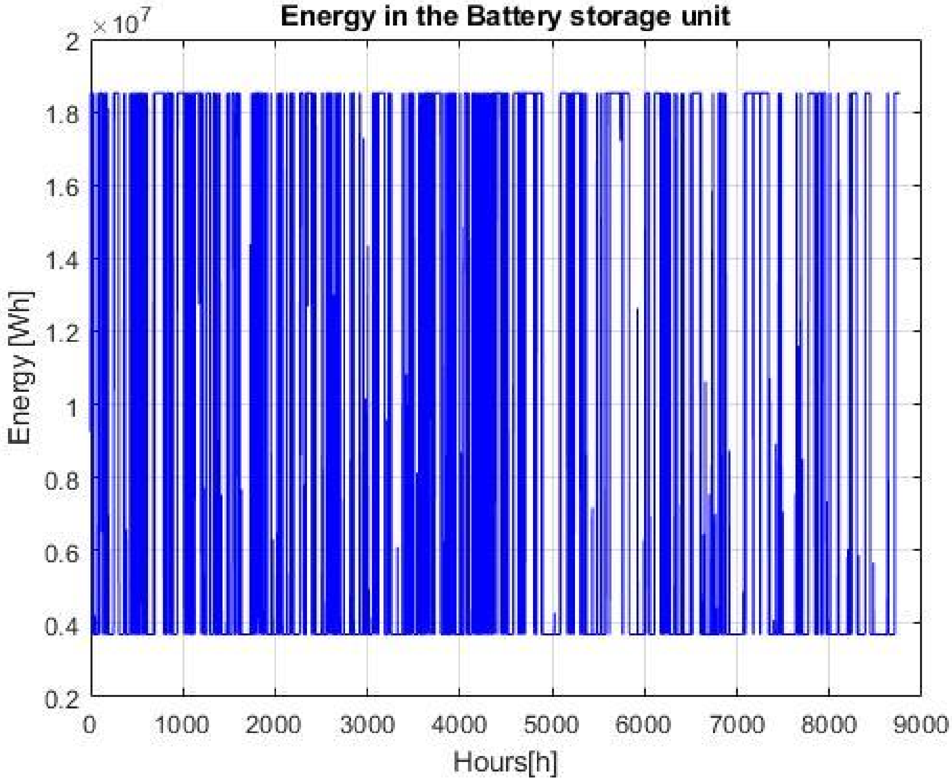

Figure 48: Hourly energy in the battery's storages in Lesbo

The fuel cells are also accompanied by batteries for the supply of electricity. Figure 40 shows a continuous use of the system, which being significantly lower than hydrogen from the point of view of the installed capacity, will be the first energy supplier when the PV+WT power generation system will not be able to meet the demand.

4.6.2 COMPARISON OF THE ENERGY STORED

The following graph depicts the comparison between the stored energy with respect to that available from the surplus, produced by the system of solar panels and wind turbines, for the four islands analyzed.

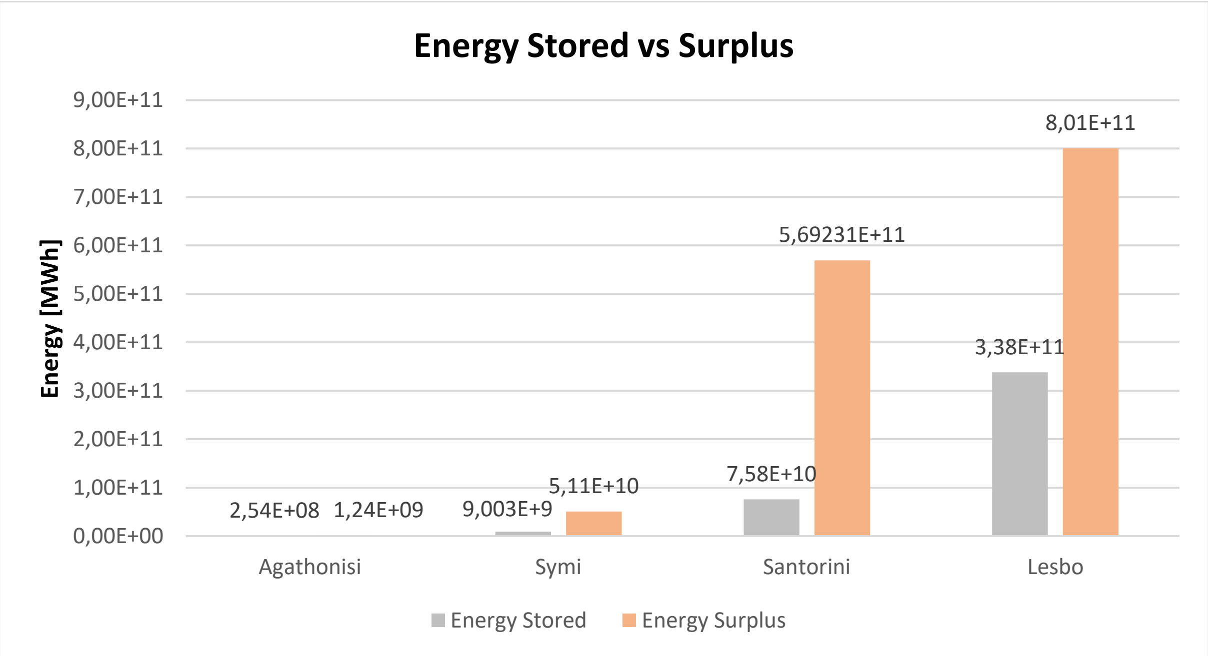

Figure 49: Energy stored vs surplus for the islands

As expected, the first three islands follow a decreasing trend. The percentages relating to the exploitation of surplus energy in fact decrease from 20% of Agathonisi, to 17% of Symi, to conclude at 13% of Santorini. Lesbos, with a value equal to 41% of energy used, is instead in total contrast to what was obtained. A deviation from the expected trends was already evident from Figure (), where the highly variable trend of hydrogen inside the storage let us imagine a continuous need for energy on the part of the island. Other reasons are attributable to the morphology of the island itself and the availability of energy sources such as wind. Previously, it was in fact highlighted that Lesbos did not enjoy a constant availability of the minimum wind speed for the activation of wind turbines. All these factors result in a surplus energy production by the power generation system not too far from that of Santorini, where however the difference in the required energy load results in the continuous activation of the system, not being able to increase the sizes of the components as it would increase the cost of energy generation associated with them.

4.6.3 ONLY H_2 LAYOUT

The layout case with the sole presence of a hydrogen storage system has values similar to the optimal case.

Solution with only H2 storage	
LPSP	0
H2 Storage System [kWh]	33561000
Battery Storage System [kWh]	0
Electrolyzers System [kW]	407380
Fuel Cells System[kW]	55410
PV System[kW]	0
Wind Turbines System [kW]	840400

Table 19: Lesbo's layout with only H2

Contrary to what one might imagine, the capacity of the hydrogen tank is reduced to 3,35 [GWh]. This difference is due to the increase in the wind farm of 10 [MW] of installed power, up to a total 840,4 [MW]. The fuel cell system does not undergo significant changes, while electrolysers rise from 394,4 [MW] to 407 [MW] which gives a greater conversion of electricity into H_2. In general, all component values differ very little from their respective optimal case values. This leads to a trend of hydrogen inside the storage and consequently to an activation of fuel cells like those seen previously.

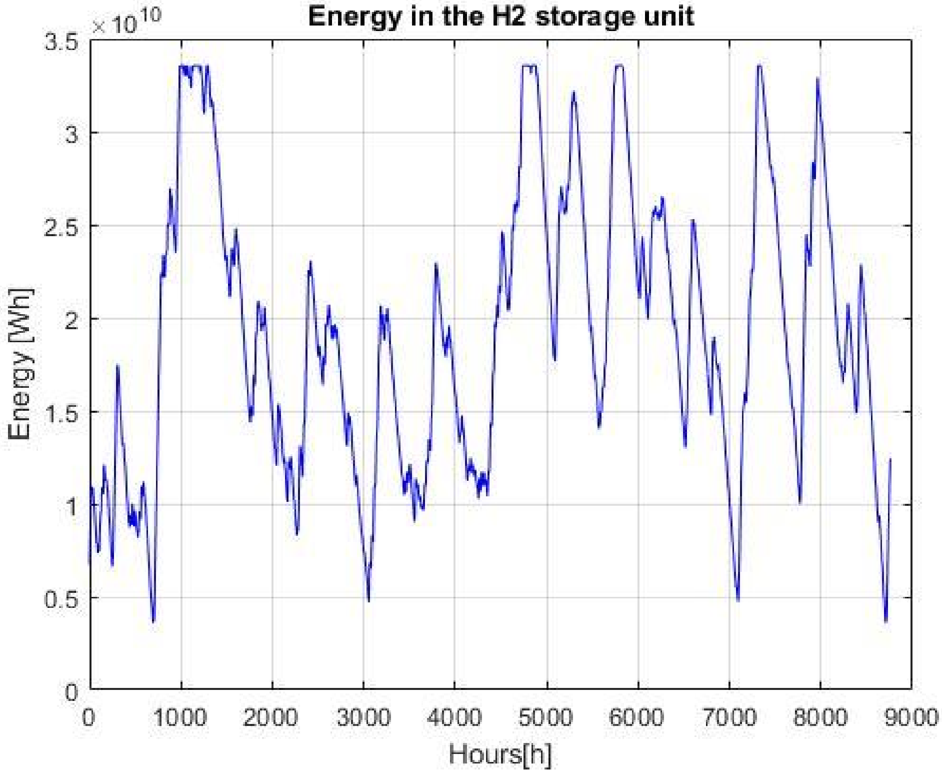

Figure 50: Hourly energy in the H2 storage of Lesbo in case of only hydrogen utilization

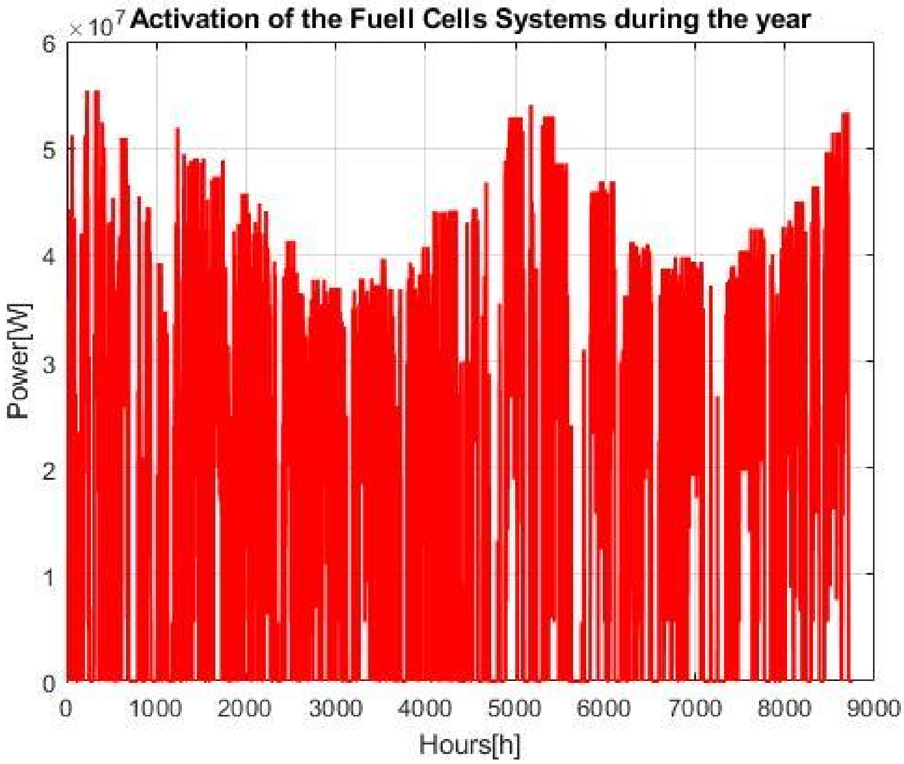

Figure 51: Hourly activation of the fuel cells system in Lesbo in case of only hydrogen utilization

4.6.4 ONLY BATTERIES LAYOUT

The table shows the results obtained when using batteries only.

Solution with only Batteries	
LPSP	0
H2 Storage System [kWh]	0
Battery Storage System [kWh]	3697200
Electrolyzers System [kW]	0
Fuel Cells System[kW]	0
PV System[kW]	827330
Wind Turbines System [kW]	391030

Table 20: Lesbo's layout with only batteries

The presence of only batteries as a storage system leads to the need to increase the total installed power. As for the other islands, it will therefore be necessary to design a hybrid system, divided into 827,33 [MW] in a photovoltaic field and 391 [MW] in a wind farm for a total of 1,218 [GW]. The system is completed by a 3,697 [GWh] battery system.

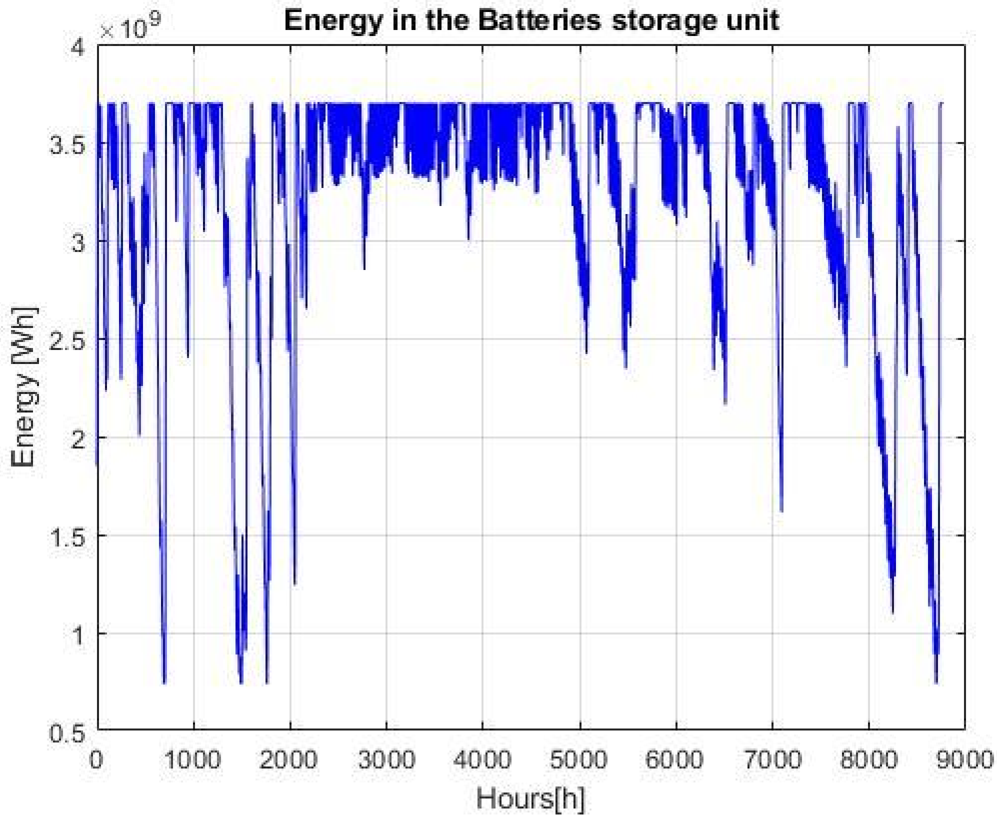

Figure 52: Hourly energy in the storage in Lesbo in case of only batteries utilization

The annual trend of energy within the storage shows an anomalous trend compared to those seen so far. As for the other islands, one would expect a uniform trend or localized peaks in the summer period. For Lesbos, however, the peaks of energy required are mainly concentrated in the period between September and January. An explanation of this trend could be the partial absence of production of the photovoltaic field in the period of interest. At the same time, the constant presence of the sun in the summer allows the system to work at its best, consuming directly the energy produced by the panels during the hours of daylight.

5 ECONOMIC ANALISYS

Having obtained the various configurations and the respective sizes of the individual components for each island, the sizing of the systems is completed. However, in order to demonstrate the validity of the project, its feasibility must also be demonstrated from an economic point of view. This section will illustrate the various steps that made it possible to obtain the quantities of money involved and the relative conclusions on the feasibility of the various plants, assuming that they operate for 20 years.

5.1 FIXED COSTS

Before performing the economic analysis and obtaining the cash flows involved, it is necessary to know the fixed costs that each component of the system has. The fixed costs include the price of the technology itself, the cost due to its transport and installation, the cost due to its replacement and the related expense due to the new transport and installation. It is also essential to know the life span of the component under analysis, as its replacement will depend on it, and the costs associated with maintenance.

5.1.1 POWER SYSTEM

PV system		
Capex due to PV panels	c_capex_PV_panels [€/kW]	1133,33
Capex due to transport and installation	c_capex_PV_transp_inst [€/kW]	320
Cost of replacement of PV panels	c_rep_PV_panels [€/kW]	680
Cost of replacement due to transportation and installation	c_REp_transp_inst [€/kW]	360
PV lifetime	life_PV [y]	25
Operation and mainteance PV	OM_PV [€/kW/y]	20

Table 21: PV system's fixed cost

The costs associated with the photovoltaic system are derived from the chosen technology. The choice of using modules produced in mono crystalline silicon raises the price to 1133,33 [€/kW], but its duration guaranteed for 25 years with a very low reduction in efficiency balances the investment, having no costs related to replacement of modules. Other non-negligible costs are related to the operations and constant maintenance that the PVs require, leading to a considerable increase in the total price for their use.

Inverter of the PV system		
Capex_inverter	c_capex_inv [€/kW]	93,33
Cost of replacement of the inverter	c_rep_inv [€/kW]	80
Lifetime of the inverter	life_inv [y]	10
Operation and maintenance of the converter	OM_inv [€/kW/y]	4

Table 22: Inverter's fixed costs

The inverter, which the photovoltaic system needs to convert energy from direct current to alternating current, is associated with much lower costs. However, as it is a delicate component, it requires more frequent replacement (10 years), impacting on replacement costs. Furthermore, by increasing the size of the PV system, the costs of the inverter would increase proportionally, affecting the total installation cost in a non-negligible way.

Wind system		
Wind capex	c_capex_wind [€/kW]	1175
Wind replacement cost	c_rep_wind [€/kW]	723
Wind lifetime	life_wind [y]	25
Operation and maintenance wind	OM_wind [% of inv cost]	3

Table 23: Wind system's fixed costs

The same considerations made for photovoltaic panels apply to wind turbines. The installation (1175 [€/kW]) and replacement (723 [€/MWh]) prices do not differ much from the PV and also the duration of the technology can be considered the same. The difference is in the operational and maintenance costs. In technologies that exploit the wind, unlike solar, these costs are actually not considered fixed, but rather linked to their investment cost. For this analysis, an operation and maintenance price equal to 3% of the capex was assumed; a percentage that could significantly increase the final cost in case it was necessary to install a large wind farm.

5.1.2 STORAGE SYSTEM

Fuel Cells		
Reference size	S_0_fc [kW]	10
Reference specific cost	c_0_fc [$/kW]	4381
Reference specific cost	c_0_fc [€/kW]	c_0_fc/1,11
Reference cost	C_0_fc [€]	c_0_fc*10
Cost exponent	n_cost [-]	0,7
Capex of the fuel cell system	c_capex_PEM_fc_system [€/kW]	1978,1
Cost of replacement of the PEM fuel cell stack	c_rep_PEM_fc_stack [% of CAPEX]	26,67
Lifetime of the PEM fuel cell stack	life_PEM_fc_stack [y]	5
Operation and maintenance of the PEM fuel cell system	OM_PEM_fc [% of investment]	3

Table 24: Fuel cells fixed costs

The high costs of fuel cells are mainly linked to their not total affirmation on a world scale. Being a relatively young technology and still under development and continuous evolution, their prices are consequently unable to compete with those of other RESs. The installation price of 1978,1 [€/kW] was calculated and kept constant for plants requiring an installed power of this technology exceeding 110 [kW]. For the island of Agathonisi, for which the size of the fuel cells was below the threshold value, the installation cost was instead obtained from equation (6):

$$\text{c\_capex\_PEM\_fc\_system} = \frac{C\_0\_fc * \left(\frac{P_{FCnom}}{S_{0_{fc}}}\right)^{n\_cost}}{P_{FCnom}} \qquad (6)$$

Where P_{FCnom} represents the power in kW required by the optimization algorithm for the fuel cells of the island under analysis.

The costs of replacing the stack, to be carried out every 5 years, and those for system maintenance, equal to 26,67% and 3% of the installation cost respectively, contribute significantly to the increase in the total investment cost.

Electrolyzers		
Electrolyzers system capex	c_capex_el_system [€/kW]	1224,581
Cost of replacement of the electrolyzer stack	c_rep_el_stack [% of CAPEX]	26,67
Lifetime of the electrolyzer stack	life_el_stack [y]	5
Operation and maintenance of the electrolyzer system	OM_el [% of CAPEX/y]	3

Table 25: Electrolyzers fixed costs

Electrolysers follow the previous considerations on fuel cells, as they are also a technology under development. The cost of 1224,58 [€/kW] was obtained by setting the system to a threshold value equal to 2 MW and keeping it fixed for systems that exceeded this condition. As with fuel cells, Agathonisi was the only island to fall below the threshold.

The installation cost associated with the group of electrolysers was calculated through equation (7):

$$\mathrm{c\_capex\_el\_system} = 26401 * \mathrm{P_{ELnom}}^{-0{,}404} \qquad (7)$$

Where $\mathrm{P_{ELnom}}$ represents the power in kW required by the optimization algorithm for the electrolysers of the island under analysis.

The electrolysers also need to be replaced every 5 years, with replacement and maintenance costs equal to the fuel cells and equal to 26,67% and 3% of the installation cost.

Hydrogen Storage		
Lower heating value H2	LHV_H2 [MJ/kg]	119,96
Mass of hydrogen in the storage	mass_H2 [kg]	E_ACC*3,6*LHV_H2
Capex of the hydrogen tank	c_capex_H2_tank [€/kg]	470
Cost of relacement of the hydrogen tank	c_rep_H2_tank [€/kg]	470
Lifetime of the hydrogen tank	life_H2_tank [y]	35
Operation and maintenance of the hydrogen tank	OM_H2_tank [% of CAPEX/y]	2

Table 26: Hydrogen storage's fixed costs

The costs related to the hydrogen tank are strictly linked to the quantity of substance that it must contain. For the analysis, a fixed installation cost of 470 [€/kg] is considered and the long life of the component (35 years) guarantees to avoid replacement for the entire duration of the analysis. Since the results of the optimization algorithm showed that most optimal configurations would rely only on hydrogen, it is immediate to expect this component to have a large impact on the total installation cost.

Batteries Storage		
Battery capex	c_capex_bat [[€/kWh]	550
Cost of replacement of the battery	c_rep_bat [€/kWh]	550
Lifetime of the battery	life_bat [y]	10
Operation and maintenance of the battery	OM_bat [€/kWh/y]	10

Table 27: Batteries storage's fixed costs

The comparison between the two energy storage technologies shows that batteries are the most expensive solution. The higher installation and replacement costs compared to hydrogen (550 [€/kWh]) and the need to replace them every 10 years would in fact lead to an increase in the plant's LCOE, making it not efficient compared to current technologies from a monetary point of view.

5.2 TOTAL INVESTMENT COST AND NPV

Once the fixed costs for each component of the system have been defined, it is possible to perform the true economic analysis. For Agathonisi, Symi and Santorini, the results relating to the optimal configurations and cases with only the use of batteries as an energy storage system will be reported. For Lesbos, the configuration with the sole use of hydrogen as a storage method will be added to the cases already mentioned.

The analysis will follow the following steps:

- Calculation of the total installation cost (CAPEX): The costs related to its installation will be calculated for each component, starting from the data relating to the sizes obtained in section 3 of the report. These values will be multiplied by the related fixed costs obtaining the CAPEX of each component.

$$Capex_{comp}\,[€] = Fixed\ cost_{comp} * Size_{comp} \quad (8)$$

The total installation cost is obtained from the sum of the Capex for each component:

$$Capex_{tot}[€] = \sum_{i=1:7} Capex_{comp}\,(i) \quad (9)$$

- Calculation of total operational costs (OPEX): They represent all the expenses that the plant will have to incur each year, thus including all the operations that fall within the operation and maintenance of the plant. The values associated with the individual components are first calculated within the optimization algorithm within a "for" loop and then added together to obtain the total over the 20 years:

$$Opex_{comp}[€] = \sum_{i=1:20} Opex_{comp}\,(i) \quad (10)$$

The total operational cost will be obtained from the sum of the Opex for each component:

$$Opex_{tot}[€] = \sum_{i=1:7} Opex_{comp}\,(i) \quad (11)$$

- Calculation of the total costs of replacing components (REPLACEMENT): They represent the cash flow associated with the replacement of the components that require to be replaced during the assumed life of the system (20 years):

$$Replacement_{comp}[€] = \sum_{i=1:20} Replacement_{comp}\,(i) \quad (12)$$

$$Replacement_{tot}[€] = \sum_{i=1:7} Replacement_{comp}\,(i) \quad (13)$$

Once the 3 results are obtained, the total cost of the plant in its 20 years of operation will be:

$$Total\ Cost\ [€] = Capex_{tot} + Opex_{tot} + Replacement_{tot} \quad (14)$$

5.2.1 AGATHONISI RESULTS

	Optimal Case			
	CAPEX [€]	**OPEX [€]**	**REPLACEMENT [€]**	**TOTAL COST [€]**
PV System	305200	52779	0	357979
Inverter	19599	10556	10411	40566
Wind System	452375	170540	0	622915
Electrolyzers	374260	141090	189090	704440
Fuel cells	237690	89608	120090	447388
Hydrogen tank	409040	102800	0	511840
Batteries	0	0	0	0
Tot [€]	1798164	567373	319591	2685128
LCOE [€/MWh]	320			

Table 28: Total investment cost for Agathonisi in the optimal case

The results of the economic analysis of the optimal layout of Agathonisi's island require an installation cost for the plant of 1,798 million euros and a total cost over the 20 years of the plant's life equal to 2,685 million euros. Assuming a connection to the nearest electrical grid via submarine cables, the cost would be decidedly higher as it is estimated at 1000000 [€/km] [7]. It has also been shown that the expansion of the electricity network cannot exceed 25 km, to keep the investment financially effective and being very distant from both the Greek coasts and other larger islands, it would not be possible to expand the electricity network only to electrify this island. The proposed solution is therefore very advantageous. Another parameter that confirms the feasibility of the project is the LCOE value of 320 [€/MWh]. Compared with the cost currently paid by the island to generate electricity (891,38 [€/MWh], see section 2.1) it has decreased by almost 2/3 potentially leading to enormous savings for the island.

	Only Batteries Solution			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	1431500	247560	0	1679060
Inverter	91930	49512	48830	190272
Wind System	129250	48726	0	177976
Electrolyzers	0	0	0	0
Fuel cells	0	0	0	0
Hydrogen tank	0	0	0	0
Batteries	1056000	241280	654380	1951660
Tot [€]	2708680	587078	703210	3998968
LCOE [€/MWh]	468			

Table 29: Total investment cost for Agathonisi in case of only battery-powered storage

Even the layout that requires only the use of the battery system would be advantageous for the island. The LCOE value of 468 [€/MWh] would still lead the island to significantly save on electricity generation. However, it differs greatly from the result obtained in the optimal case and also the high total cost of the plant (almost 4 billion euros) leads to a preference for the first solution.

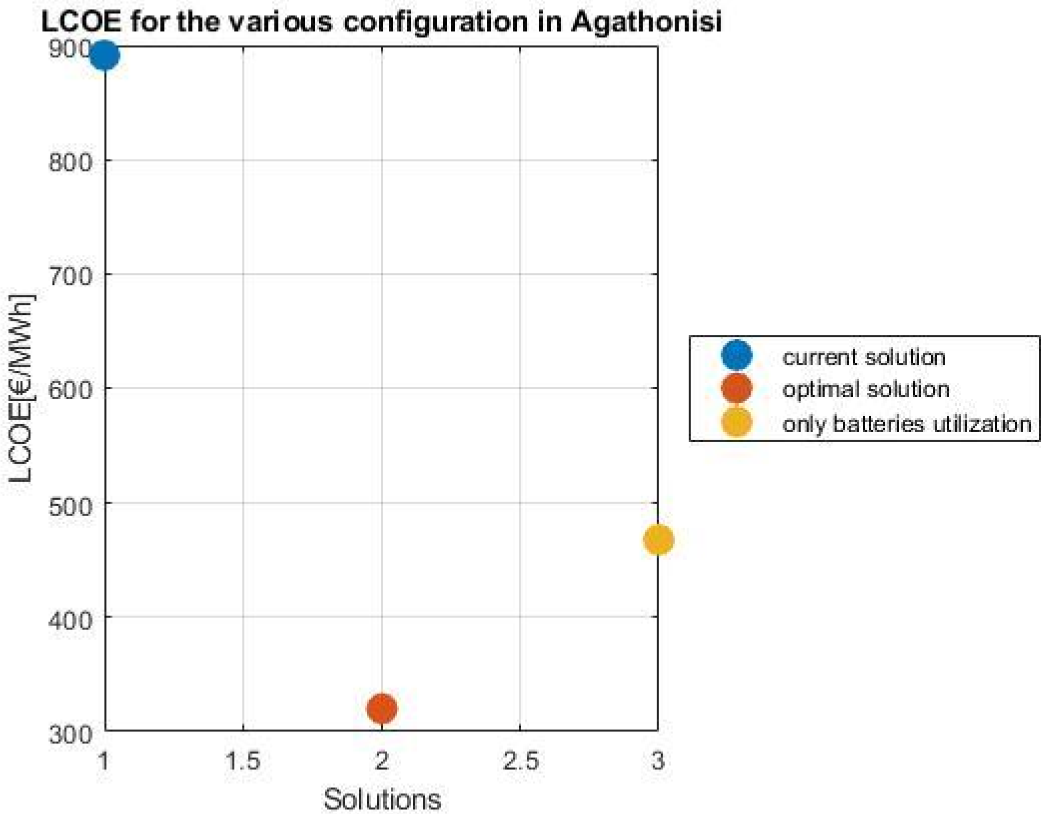

Figure 53: LCOE comparison for Agathonisi

For the optimal layout of the island, the Net Present Value (NPV) was also calculated, which expresses the difference between the present value of the incoming cash flows and the present value of the outgoing cash flows over a period of time. Its trend is obtained from the cash flow that occurs every year for the plant:

$$Cash\ Flow\ (i)[€] = Revenues - Cost\ of\ el\ - Capex\ - Opex\ - Replacement \quad (15)$$

Where:

- Revenues: Money saved by not generating electricity in the conventional way (891.38 [€/MWh] * 727 [MWh/y]) every year.
- Cost of el: Expenditure due to the new generation cost (320 [€/MWh] * 727 [MWh/y]) each year.
- Capex: Annual investment cost, equal to the total CAPEX for the first year and 0 in the following.
- Opex: Annual operational costs.
- Replacement: Costs due to the replacement of some components in certain years.

The cash flow obtained will therefore be a vector composed of 20 elements, from which the cumulative NPV is obtained (16):

$$NPV(i) = Cash\ flow(i) + NPV(i-1)$$

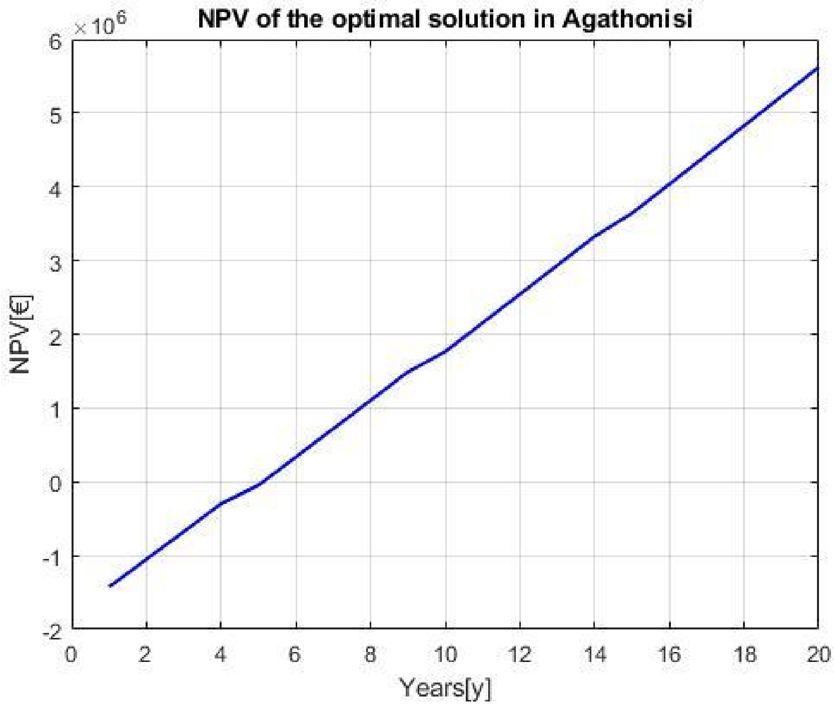

Figure 54: NPV of Agathonisi's plant in case of installation in 2020

The trend starts from year 1 at a value below zero as it is influenced by the total CAPEX of the plant, and then grows linearly up to a value of approximately 5,7 billion after 20 years, corresponding to the potential gain that the plant would lead. The payback time is reached in about 5 years.

5.2.2 SYMI RESULTS

	Optimal Case			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	13079970	2262000	0	15341970
Inverter	839970	452390	446170	1738530
Wind System	14100000	5315600	0	19415600
Electrolyzers	7152420	2696400	3613700	13462520
Fuel cells	15824800	5965900	7995400	29786100
Hydrogen tank	4253900	102800	0	4356700
Batteries	0	0	0	0
Tot [€]	55251060	16795090	12055270	84101420
LCOE [€/MWh]	354			

Table 30: Total investment cost for Symi in the optimal case

Proportionally to the increase in the annual energy load required, for Symi the costs related to installation, operational and replacement increase significantly, reaching a total of 84,1 million euros over the life of the plant. The LCOE value of 354 [€/MWh] does not differ much from the current generation cost of 386,36 [€/MWh] (see section 2.1.2), making it not convenient to invest at today's market prices in such technology. It would in fact be cheaper to connect the island to the micro-grid on the island of Rhodes, about 60 [km] away, but even this solution is not viable due to the excessive distance.

	Only Batteries Solution			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	40693240	7037200	0	47730440
Inverter	2613240	1407400	1388100	5408740
Wind System	9400000	3543700	0	12943700
Electrolyzers	0	0	0	0
Fuel cells	0	0	0	0
Hydrogen tank	0	0	0	0
Batteries	54780000	14074000	33946000	102800000
Tot [€]	107486480	26062300	35334100	168882880
LCOE [€/MWh]	588			

Table 31: Total investment cost for Symi in case of only battery-powered storage

The analysis of the layout with the mere presence of batteries brings out a much higher LCOE than the previous one (588 [€/MWh]) which makes it not convenient to implement this solution.

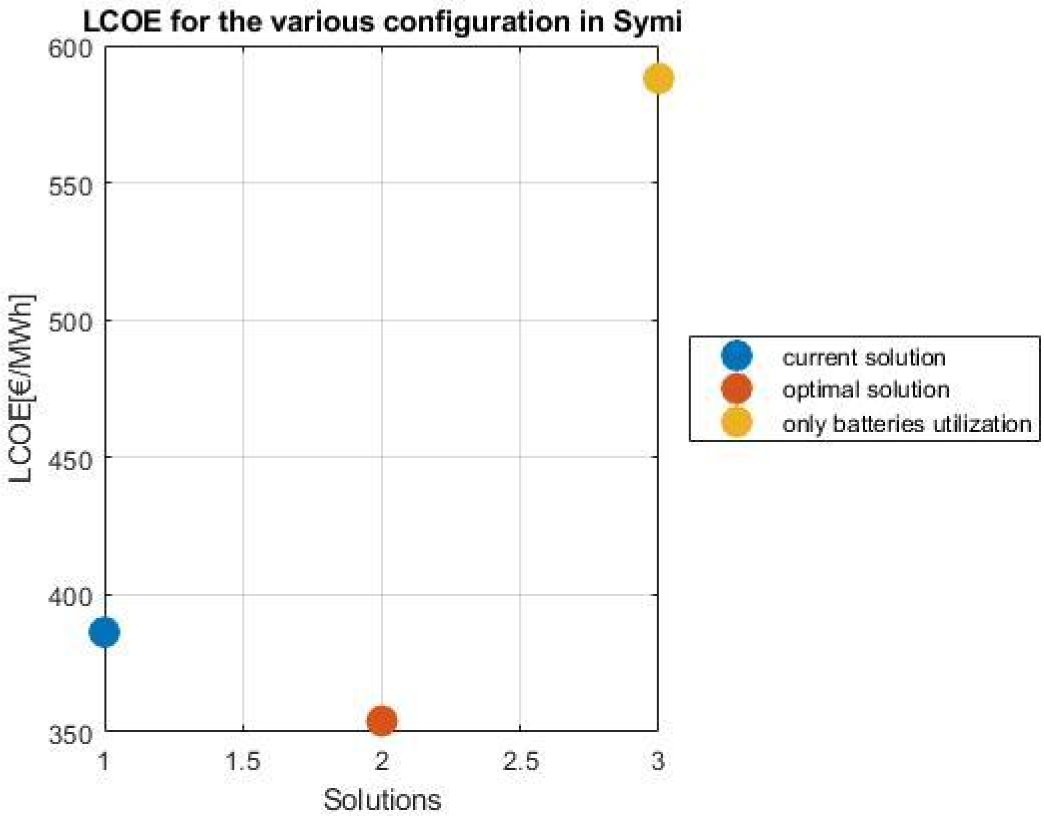

Figure 55: LCOE comparison for Symi

In Figure 45 is showed the NPV trend for the Symi island in the case of optimal layout.

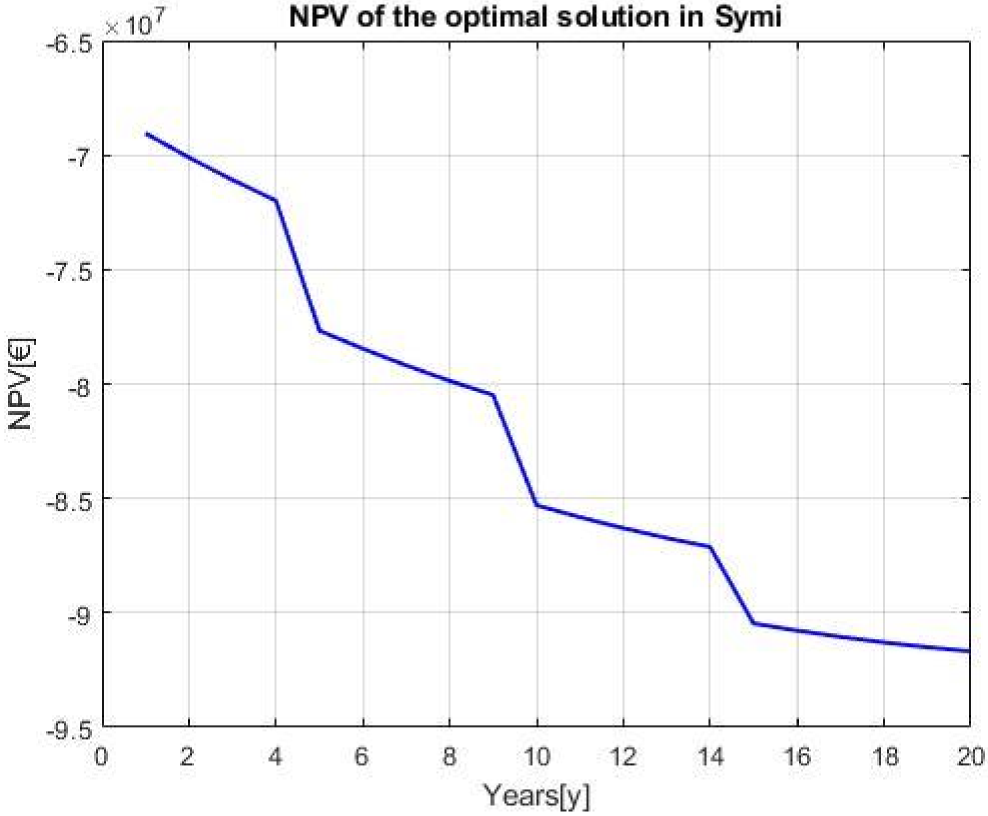

Figure 56: NPV of Symi's plant in case of installation in 2020

The NPV never reaches the payback time, instead decreasing more and more. The explanation lies in the too small difference between the LCOE values between the proposed solution and the one currently installed. The cash flow that would be earned does not manage to balance the necessary expenses leading to a continuous loss of money. Contrary to Agathonisi, in this case the trend is no longer linear, but rather composed of broken lines, representing the years in which the replacements of fuel cells, electrolysers and the inverter system for photovoltaic panels take place.

5.2.3 SANTORINI RESULTS

	Optimal Case			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	0	0	0	0
Inverter	0	0	0	0
Wind System	167061500	62981000	0	230042500
Electrolyzers	40183596	15149000	20303000	75635596
Fuel cells	70954447	26749000	35849000	133552447
Hydrogen tank	150000000	37700000	0	187700000
Batteries	0	0	0	0
Tot [€]	428199543	142579000	56152000	626930543
LCOE [€/MWh]	283			

Table 32: Total investment cost for Santorini in the optimal case

The construction of a hybrid plant capable of making Santorini totally independent from the use of fossil fuels requires an initial investment of 428,2 million euros. The figure increases if projected over the next 20 years, reaching to require approximately 627 million euros for the complete operation of the plant over time. The LCOE value of 283 [€/MWh] is also higher than the current one of 205,67 [€/MWh] (see section 2.1.3) effectively excluding the possibility of carrying out the project on this island. An explorable solution could be the connection of the island to the electricity grid on Crete. The two islands are about 200 [km] apart, a value that according to what has already been expressed for Agathonisi and Symi would not allow the connection. However, Santorini is one of the most energy-intensive islands in all of Greece, for which a more in-depth analysis would be a must.

	Only Batteries Solution			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	386004448	66753000	0	452757448
Inverter	24788448	13351000	13167000	51306448
Wind System	176250000	66445000	0	242695000
Electrolyzers	0	0	0	0
Fuel cells	0	0	0	0
Hydrogen tank	0	0	0	0
Batteries	467500000	106810000	289700000	864010000
Tot [€]	1054542896	253359000	302867000	1610768896
LCOE [€/MWh]	730			

Table 33: Total investment cost for Santorini in case of only battery-powered storage

The layout that provides for the sole use of a storage system consisting only of batteries leads to very high costs both in terms of investment, with 1,61 billion euros, and in terms of LCOE, requiring 730 [€/MWh] for the electricity production. This cost prohibits continuing to investigate such a solution even with a significant drop in prices over the next decade.

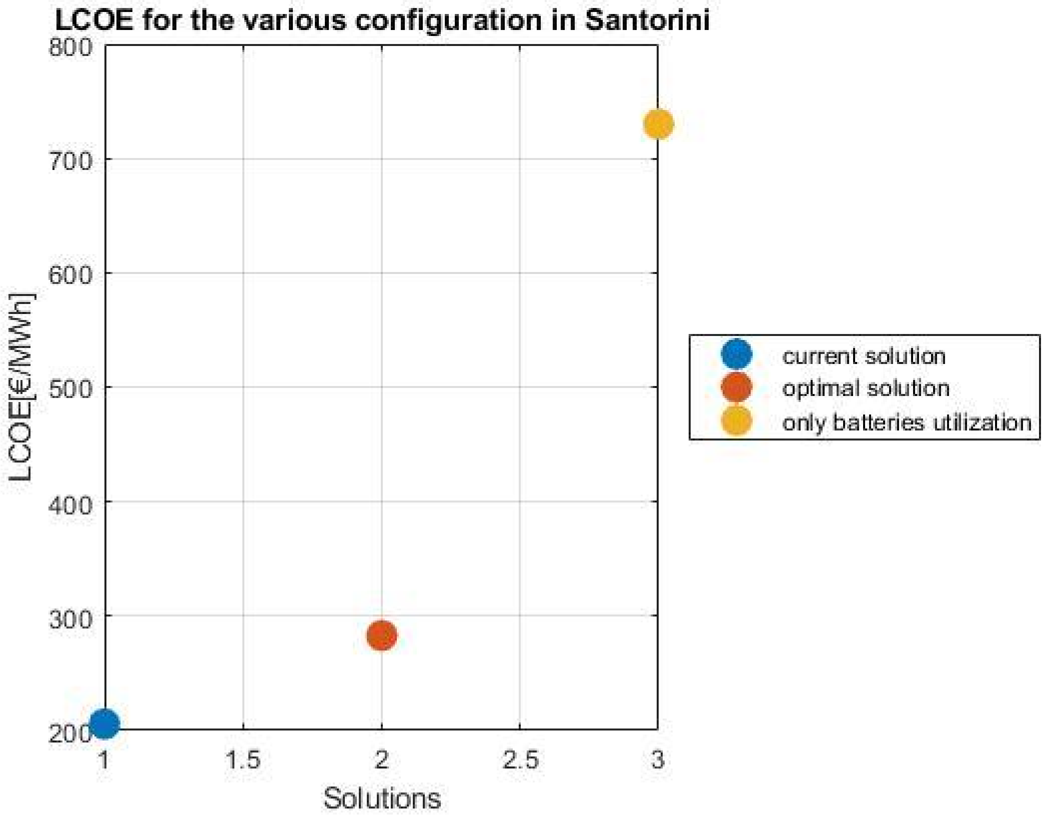

Figure 57: LCOE comparison for Santorini

As for Symi, also for Santorini, under current market conditions, the construction of the system, even in the optimal configuration, is not convenient. From a monetary point of view, the flow of money in fact continues to decrease over the years, consequently never obtaining a profit. Comparing the performance of the NPV with Symi, it is noted that in this case the segments are less evident, a sign that the costs associated with the replacement of components are relatively less influential than operating costs.

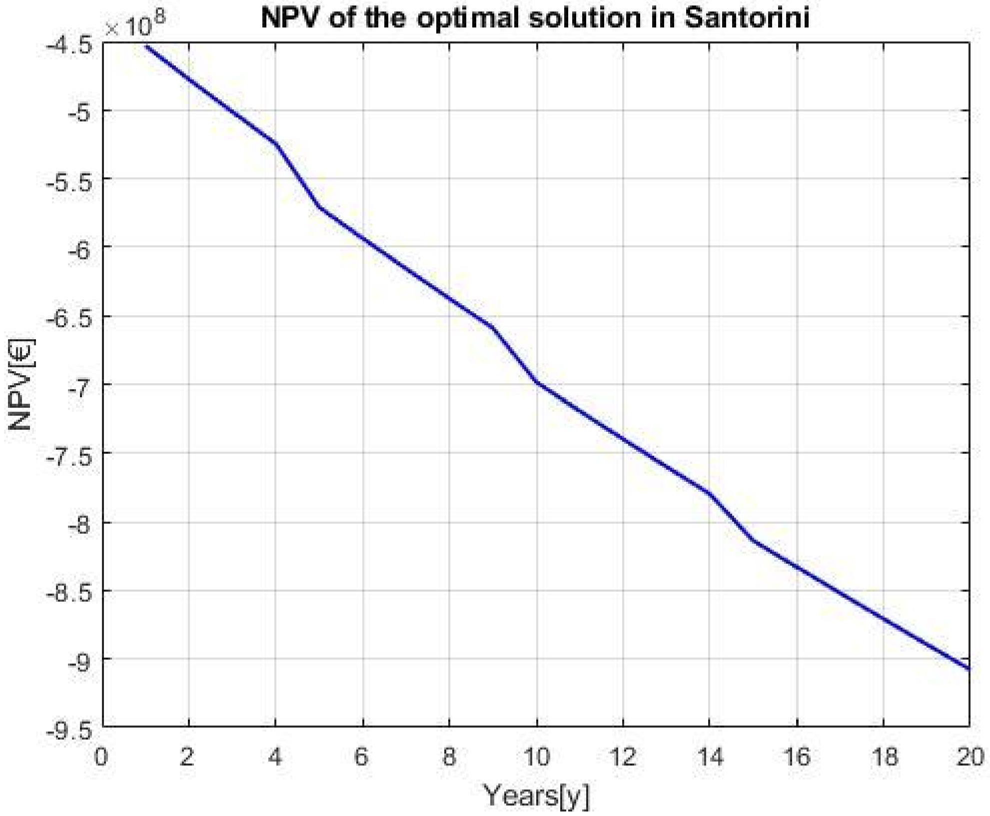

Figure 58: NPV of Santorini's plant in case of installation in 2020

5.2.4 LESBO RESULTS

	Optimal Case			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	0	0	0	0
Inverter	0	0	0	0
Wind System	975250000	367660000	0	1342910000
Electrolyzers	427302910	161090000	215890000	804282910
Fuel cells	109586740	41314000	55368000	206268740
Hydrogen tank	479560000	120530000	0	600090000
Batteries	0	0	0	0
Tot [€]	1991699650	690594000	271258000	2953551650
LCOE [€/MWh]	811			

Table 34: Total investment cost for Lesbo in the optimal case

From the analysis of the optimal layout, an LCOE value of 811 [€/MWh] emerges. This result compared with the current price paid by the island of 148,97 [€/MWh] (see section 2.1.4) shows how such a technology is not yet ready to meet such high energy loads. At present it is therefore preferable not to intervene on this island. One solution could be the expansion of the existing renewable production quota, but since most of the plants belong to private individuals, an agreement should first be found between the administration of the island and the owners.

	Only Hydrogen Solution			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	0	0	0	0
Inverter	0	0	0	0
Wind System	987470000	372270000	0	1359740000
Electrolyzers	441477706	166430000	223060000	830967706
Fuel cells	109606521	41321000	55378000	206305521
Hydrogen tank	473370000	118970000	0	592340000
Batteries	0	0	0	0
Tot [€]	2011924227	698991000	278438000	2989353227
LCOE [€/MWh]	815			

Table 35: Total investment cost for Lesbo in case of only Hydrogen storage

The proposed solution of an exclusive use of hydrogen as a storage system shows results not far from those obtained in the case of optimal configuration. The LCOE value is in fact practically identical (811 [€/MWh] against 815 [€/MWh]) and also the total costs of the plant in its life cycle are very similar, 2,953 billion euros in the first case and 2,989 billion euros in the second.

	Only Batteries Solution			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	1202400000	207930000	0	1410330000
Inverter	77215000	41586000	41014000	159815000
Wind System	459460250	173210000	0	632670250
Electrolyzers	0	0	0	0
Fuel cells	0	0	0	0
Hydrogen tank	0	0	0	0
Batteries	2033500000	464610000	1260100000	3758210000
Tot [€]	3772575250	887336000	1301114000	5961025250
LCOE [€/MWh]	1700			

Table 36: Total investment cost for Lesbo in case of only battery-powered storage

The solution proposed with only batteries proves once again the most inconvenient from an economic point of view. With an LCOE equal to 1700 [€/MWh] and a total cost of almost 6 billion euros, such a solution is once again confirmed more inconvenient than hydrogen.

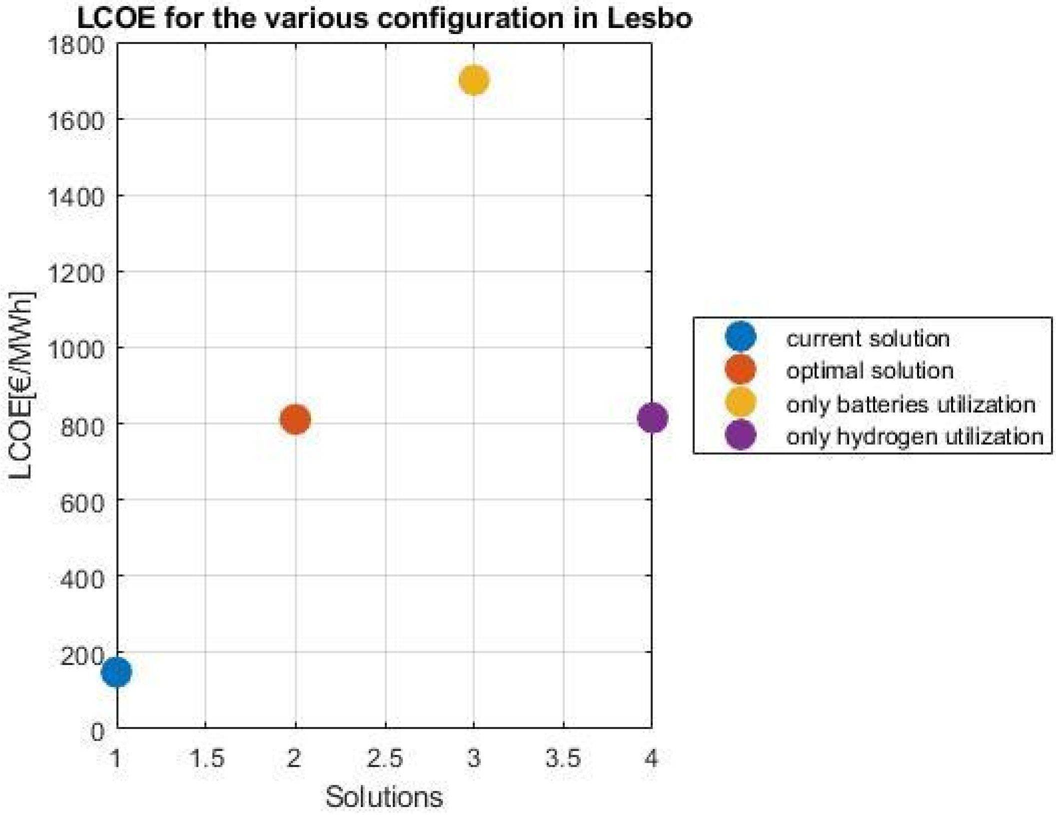

Figure 59: LCOE comparison for Lesbo

The results of the three case studies analyzed showed that for large islands and energy loads such as Lesbos, the energy transition is not yet possible. The large distances between the LCOE values compared to the price currently paid to generate energy also denies the possibility of studying the possible trend of the NPV in a future scenario. Not even with a large reduction in prices for generation from renewable sources, such as is expected for 2030, would in fact be able to make the installation of the proposed plant convenient in these islands. For this reason, the NPV trend in the optimal case has not been tracked, as well as the analysis of the same and the optimal layout projected to 2030.

5.2.5 *COMPARISON BEWEEN THE ISLANDS*

The results obtained through the economic analysis highlighted the non-feasibility of the system on Santorini and Lesbos and in general the inconvenience of using batteries as a storage system.

By analyzing the trend of the LCOE values of the current solution (blue) and those obtained from the optimal layout (red) for the four analyzed islands, it is possible to draw conclusions that can be extended to the others belonging to the same group.

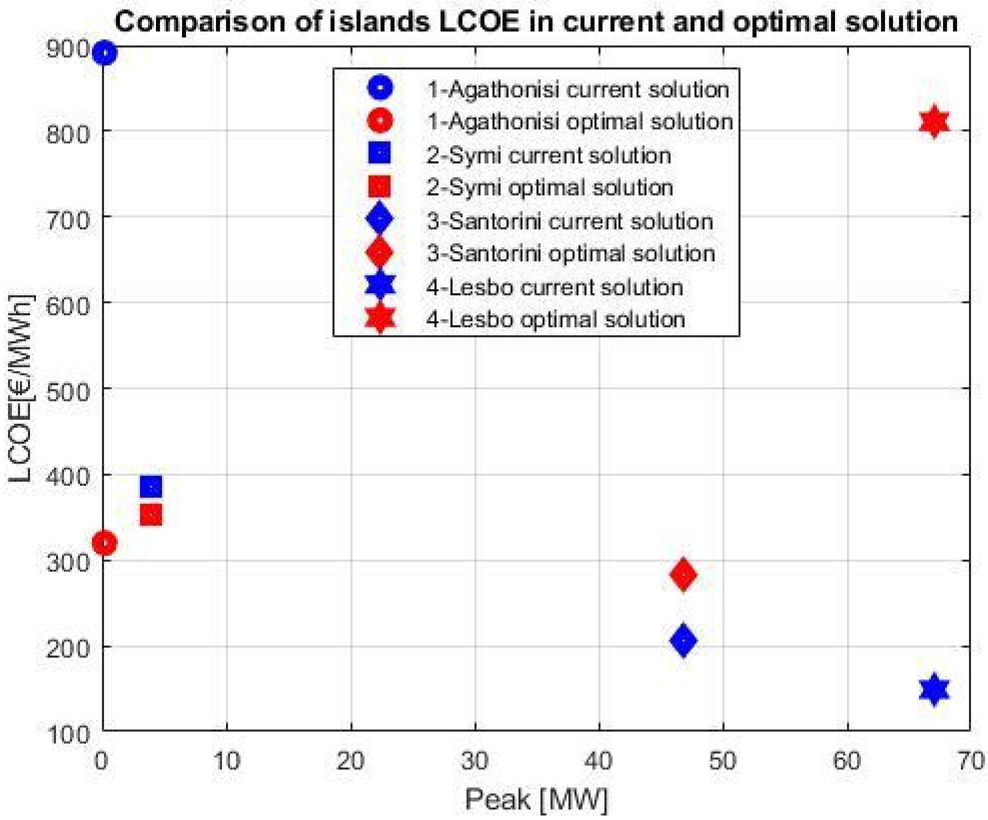

Figure 60: LCOE comparison between islands

Starting from Agathonisi and continuing in order of analysis up to Lesbos, the blue dots have a decreasing trend. This provision confirms the need of immediate intervention for the smaller islands, as they are associated with significantly higher costs to generate energy. The trend of the red dots instead shows the feasibility under the current conditions of the project. Only for the two smaller islands (Agathonisi and Symi) the LCOE values in the case of installation of the system, are below the prices currently paid. Due to the large sizes that characterize them, Santorini and Lesbos instead show negative results, compared to the solutions currently installed, as they require large sizes for the components that inevitably fall into a drastic increase in costs. It is deduced that such a technology without the intervention of incentives or a drastic reduction in components costs is currently applicable only to energy systems of small and medium-small demands.

By observing the arrangement of the current LCOE values paid by the islands, it is possible to extract a mathematical equation that describes the trend:

$$y = 570{,}85 * x^{-0{,}294} \quad (16)$$

The equation follows the characteristic trend of a decreasing exponential. It would be interesting to expand the study to understand if the model can be extended to other islands and, if so, validate it.

The trend of the results obtained through the optimization algorithm, on the other hand, seems to follow the trend of a polynomial equation such as:

$$y = 0{,}0101 * x^3 - 0{,}7471 * x^2 + 12{,}126 * x + 317{,}47 \quad (17)$$

By plotting the two equations in a single graph, it is possible to obtain a set of values within which the system would currently be installed.

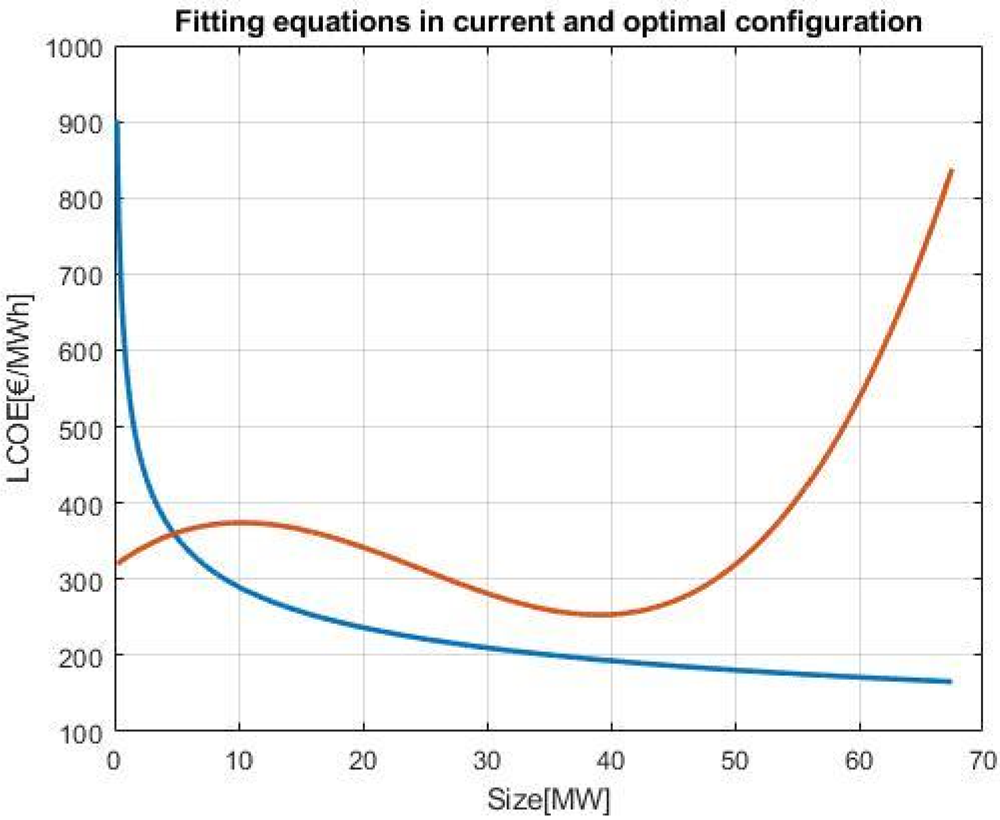

Figure 61: Fittings equations in current and optimal configuration

The intersection of the two curves occurs at the coordinates 4.9 [MW] and 361 [€ / MWh]. For all islands with a lower peak, in the case of Greece, those belonging to the first two load groups, the system would be installable and able to guarantee a price for energy generation that is less than or equal to the one currently paid. However, the results on NPV trends showed that a lower LCOE does not always mean a profit. It would be appropriate to better investigate the results in the future, once the prices of the technologies have lowered and stabilized, to try to define a certain range that allows us to establish whether the plant can actually be installed in certain remote sites.

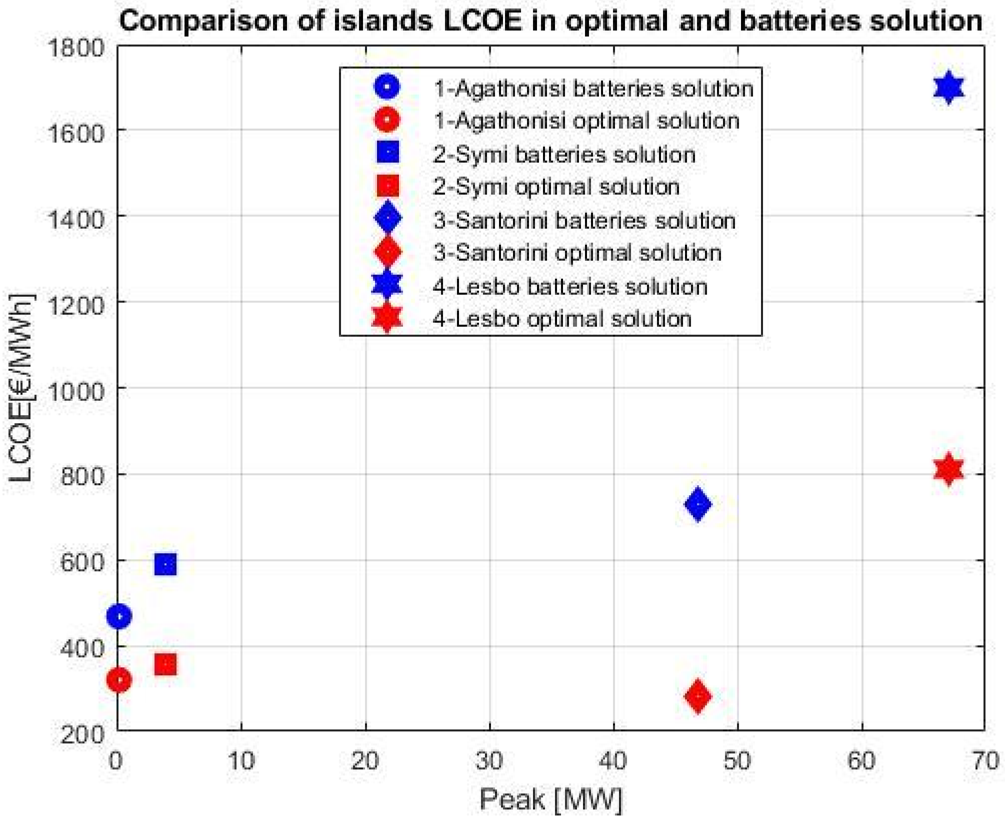

Figure 62: LCOE comparison between optimal and batteries solution

The figure represents the comparison between the results of the optimization model in the optimal case (red points) and in the hypothesized scenario with the sole presence of batteries as a storage system (blue points). As already stated above, the optimal configurations for the first three islands only involve the use of hydrogen. The main reason lies in the large price difference between the two technologies, which with the increase in the loads to be satisfied and the size of the system results in ever-increasing prices for the generation of energy. Only big incentives and price cuts, in the future, will be able to establish the use of this technology as the main energy storage system.

5.3 FUTURE SCENARIO (2030)

In anticipation of a future lowering of the prices of the technologies making up the plant, a new economic analysis was carried out for the islands of Agathonisi, Symi and Santorini, projecting the results to 2030. If for Agathonisi the results obtained with the prices currently available on the market have already shown the feasibility of the project, for the other islands the plant was too expensive and did not lead to an economic gain. Starting from these considerations, the purpose of the following analysis is to compare the results between the current situation and a hypothetical installation of 2030, in order to try to understand if the project will be expandable also to islands affected by a high load, or will remain confined. to decidedly smaller case studies.

According to estimates produced by numerous studies and by numerous multinationals operating in the energy sector, the energy transition is a process that has now begun and cannot be stopped. The prices of renewable technologies, still inaccessible to many nations today, will have to suffer a drastic and inevitable decline within the next decade to be able to compete with the much more deeply rooted fossil sources. A lowering of prices would serve not only to make these resources more accessible to many technologically more backward countries, but could gradually lead to a change of mentality in the most energy-intensive countries in the world, for which the abandonment of conventional methods of energy production it is more complicated. Starting from these considerations, the International Renewable Energy Agency (IRENA) [9] has estimated that the price of technologies based on photovoltaic panels will drop by 60%, bringing solar to meet 13% of the world's energy demand. On the same level of solar energy, expectations are also high for wind power, forecasting a cost cut of between 50% and 60% by 2030. In this way, the two main RESs installed globally would significantly expand their expansion, carving out a very important slice of the electricity market.

Significant improvements are also planned for the storage technologies. The estimates made by IRENA reveal that battery storage systems, for which continuous research is obtaining enormous results, will enjoy an increase in installed capacity by 2030 of between 155% and 227% compared to 2017, with an installed which will be around 11,9 [TWh] and 15,3 [TWh]. Prices will also undergo a large variation, estimating a fall of between 45% and 55% [15]. IRENA also provides forecasts on the future use of hydrogen-based technologies. The results of the analyzes show that approximately 700 [GW] of electrolysers will be installed by 2030. With such development and considering past technological learning rates responsible for decreasing costs, electrolyser costs should decrease by a third between now and 2030 [16]. In proportion to the decrease in the cost of electrolysers, both storage and fuel cells will have a drop in prices. For tanks, a less marked decrease is expected, while for fuel cells the expectations lead to a possible halving of the price in the next 5 years.

The results obtained with the price reductions introduced above will be reported below. Reductions of 25% have been assumed for operation and maintenance costs.

5.3.1 AGATHONISI RESULTS IN 2030

	Optimal case in 2030			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	102060	39584	0	141644
Inverter	7350	7916,9	3904	19170,9
Wind System	192500	60476	0	252976
Electrolyzers	124750	39191	15757	179698
Fuel cells	79212	24885	10005	114102
Hydrogen tank	261090	49214	0	310304
Batteries	0	0	0	0
Tot [€]	766962	221267	29666	1017894,9
LCOE [€/MWh]	119,4			

Table 37: Total investment cost for Agathonisi in the optimal case in case of installation of the plant in 2030

The results of the optimal layout of Agathonisi show a net decrease in both the LCOE and the CAPEX and consequently in the total cost of the plant over the 20 years of activity. The LCOE decreases from 320 [€/MWh] to 119,4 [€/MWh], while the total cost is reduced to just over one million euros. Calculating the NPV it was assumed to have the previously obtained system already installed and to make a replacement of all components. In this way, the result of the analysis will show the net gain that would be obtained starting from 2030. The value currently paid by the island of 891,38 [€/MWh] was therefore not used for the calculation of the saved capital, but rather 320 [€/MWh] previously obtained. The further gain that the island could have from the depreciation of technologies would amount to 2 million euros.

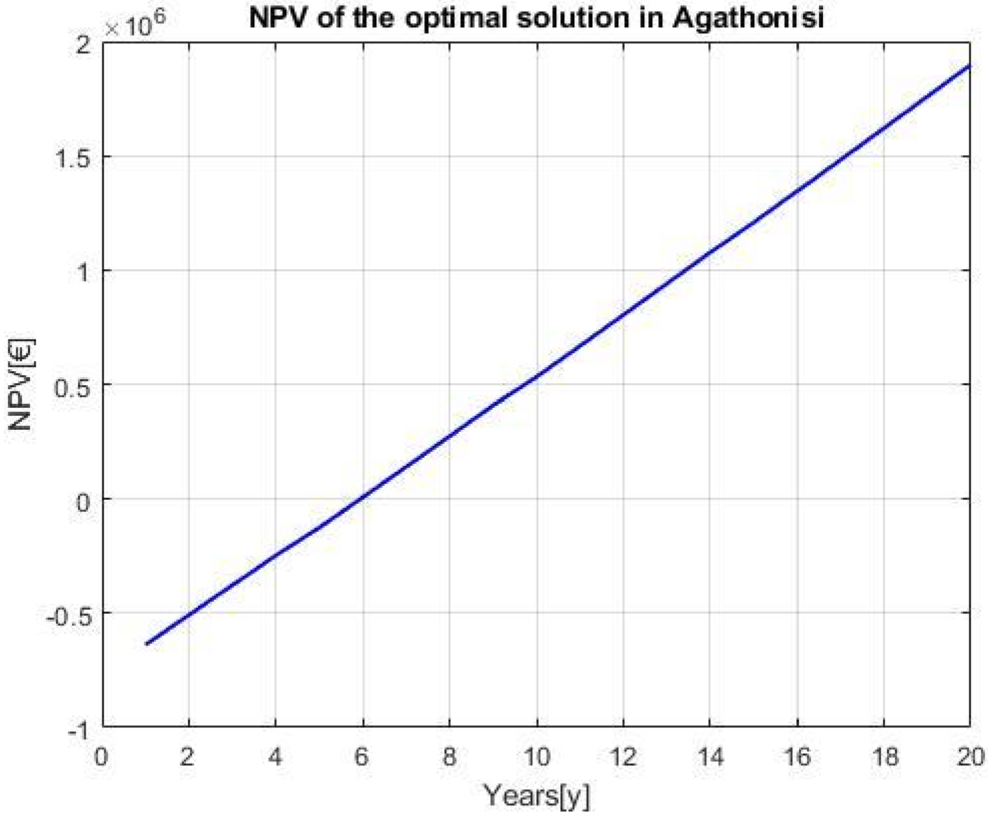

Figure 63: NPV of Agathonisi's plant in case of installation in 2030

5.3.2 SYMI RESULTS IN 2030

	Optimal case in 2030			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	4374000	1696500	0	6070500
Inverter	315000	339290	167310	821600
Wind System	6000000	1885000	0	7885000
Electrolyzers	1471800	462390	185910	2120100
Fuel cells	1416400	444990	178910	2040300
Hydrogen tank	10804000	2036400	0	12840400
Batteries	0	0	0	0
Tot [€]	24381200	6864570	532130	31777900
LCOE [€/MWh]	111			

Table 38: Total investment cost for Symi in the optimal case in case of installation of the plant in 2030

Symi was characterized by an LCOE very close to the current cost of generation using diesel engines, respectively 354 [€/MWh] and 386,36 [€/MWh] (see section 4.2.2). The prices assumed by the projections to 2030 would lead to obtain a significantly lower LCOE value equal to 111 [€/MWh]. Such a result certainly positively influences the trend of the cash flow. Previously, in fact, the island's NPV trend continued to decline over the years. The new trend of the NPV (Figure 48) shows that by starting the installation of the plant in 2030, the island could even benefit from a monetary point of view. The payback time of the investment is reached in about 8 years, after which the island could earn about 40 million euros.

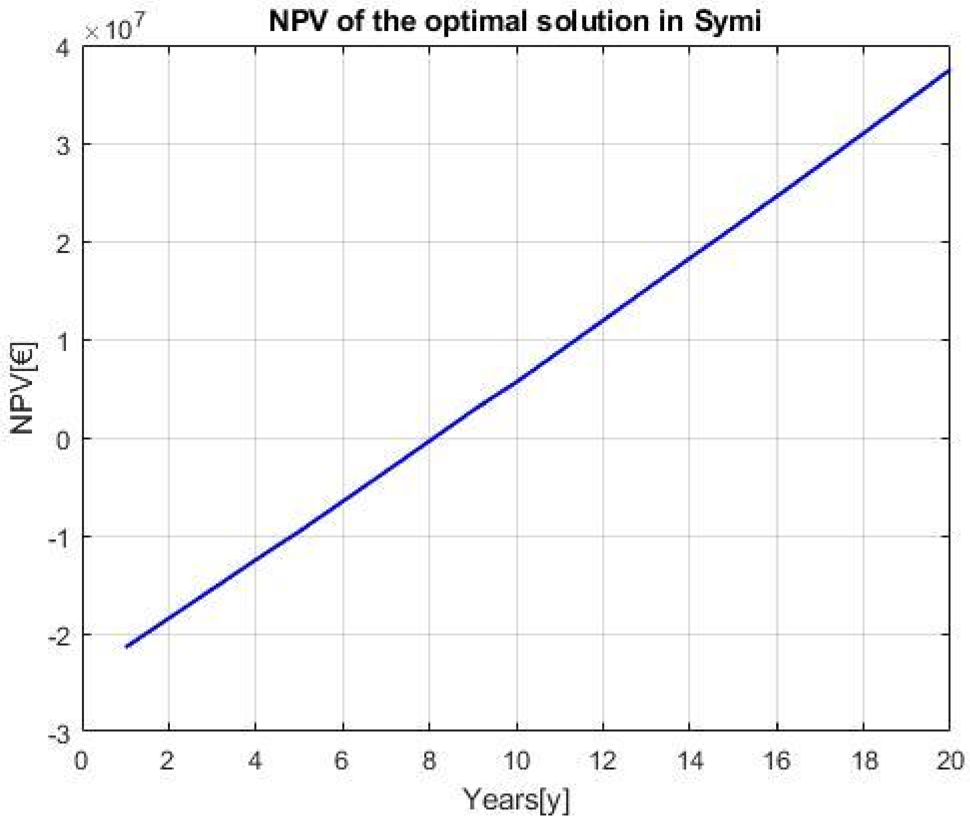

Figure 64: NPV of Symi's plant in case of installation in 2030

5.3.3 SANTORINI RESULTS IN 2030

	Optimal Case in 2030			
	CAPEX [€]	OPEX [€]	REPLACEMENT [€]	TOTAL COST [€]
PV System	0	0	0	0
Inverter	0	0	0	0
Wind System	71090000	22334000	0	93424000
Electrolyzers	4117300	1293500	520060	5930860
Fuel cells	4048900	1272000	511430	5832330
Hydrogen tank	95747000	18048000	0	113795000
Batteries	0	0	0	0
Tot [€]	175003200	42947500	1031490	218982190
LCOE [€/MWh]	98,95			

Figure 39: Total investment cost for Santorinii in the optimal case in case of installation of the plant in 2030

In this case, the main difference lies in the LCOE value. If previously the value of 283 [€/MWh] was higher than the 205,37 [€/MWh] paid by the island (see section 4.2.3), making its installation inconvenient, now, a value is obtained from the analysis equal to 98,95 [€/MWh] which makes the system installable.

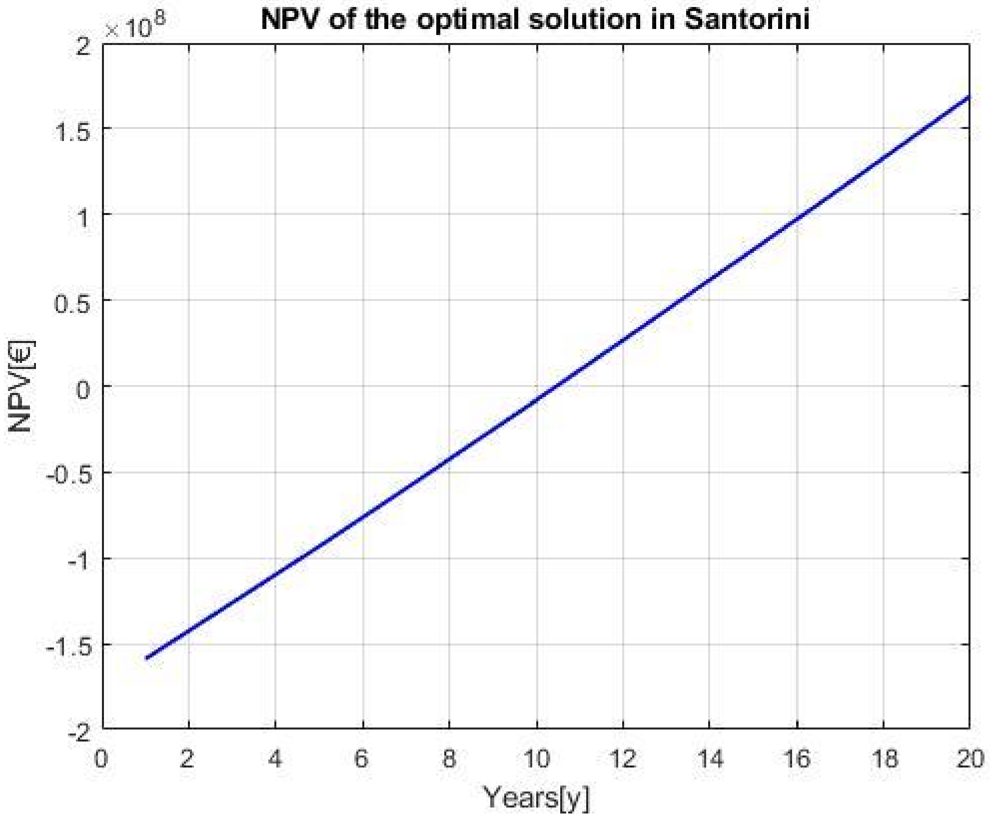

Figure 65: NPV of Santorini's plant in case of installation in 2030

The new solution would even lead to a hypothetical gain of about 170 million euros for the island, taking just over 10 years to reach the payback time. However, there remains the great problem related to the morphology of the island to be overcome, which would make the entire analysis useless. The most realistic hypothesis could be the exploitation of an offshore wind farm that would guarantee the right installation surface. To investigate this solution, more detailed analyzes of the submarine transmission system that the turbines would need would be needed, as well as an in-depth study of the island's seabed to confirm the feasibility of installation.

6 SUSTAINABILITY ANALYSIS

The following section aims to outline an overview of the potential beneficial effects for the environment that the use of the hybrid system presented could bring. The first part of the analysis is focused on the calculation of the fuel that would not be used following the installation of the plant, which is followed by the calculation of emissions, in particular equivalent CO_2, NO_x and SO_x, avoiding being released into the atmosphere. The results were extended to all islands belonging to the first three loading groups. The islands belonging to the fourth group have been excluded as the system cannot be installed on them.

6.1 FUEL CONSUMPTION

The calculation of avoided fuel consumption is the fundamental element of the analysis. In addition, being the resource for the current energy generation of the islands, through the knowledge of its chemical composition (86% C, 13% H_2, 0,6% S, 0,4% other elements) it is possible to estimate the amount of pollutants that could be avoided to produce. Assuming the exclusive use of diesel oil as a fuel for diesel engines, characterized by a calorific value equal to 11.87 [kWh/kg], through the knowledge of the energy consumption of a given island, it is possible to estimate the fuel consumption necessary to cover its energy consumption:

$$Fuel\ Consumption\ [ton] = \frac{Load\ [MWh]}{11{,}87\ \left[\frac{kWh}{kg}\right]} \quad (18)$$

The results obtained for all the islands not interconnected to the national electricity grid are illustrated below. Since it has been hypothesized to use only diesel as fuel, not having detailed information on the fuel used by each island, the results obtained will differ slightly from the real ones, however guaranteeing a fairly truthful view of the avoided consumption.

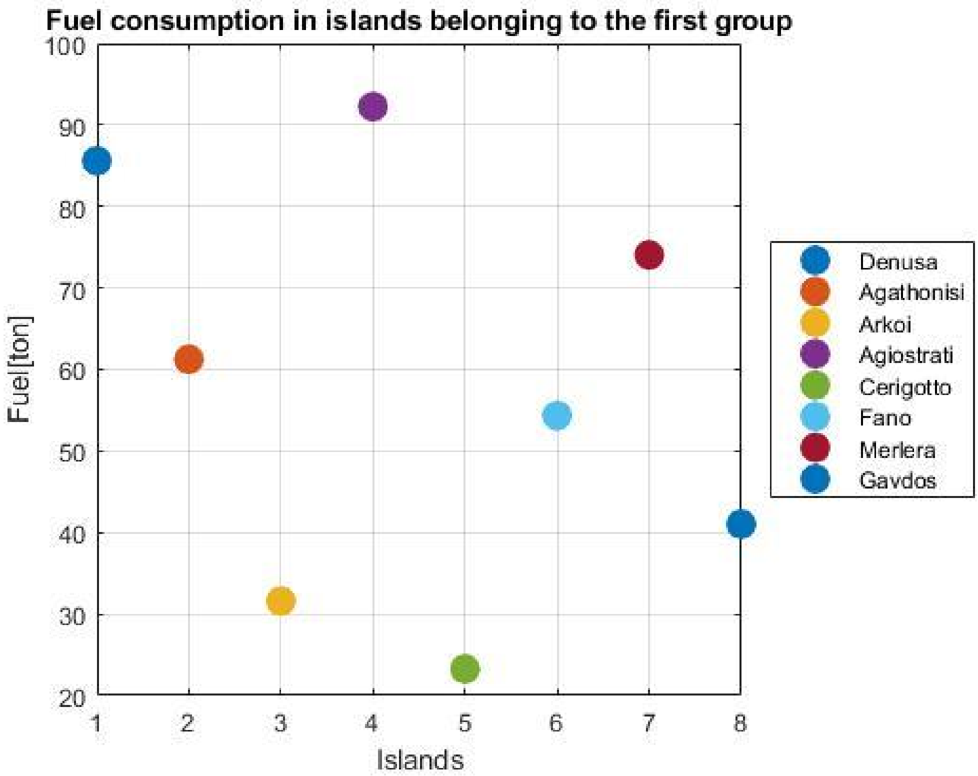

Figure 66: Fuel consumption for islands belonging to the first group

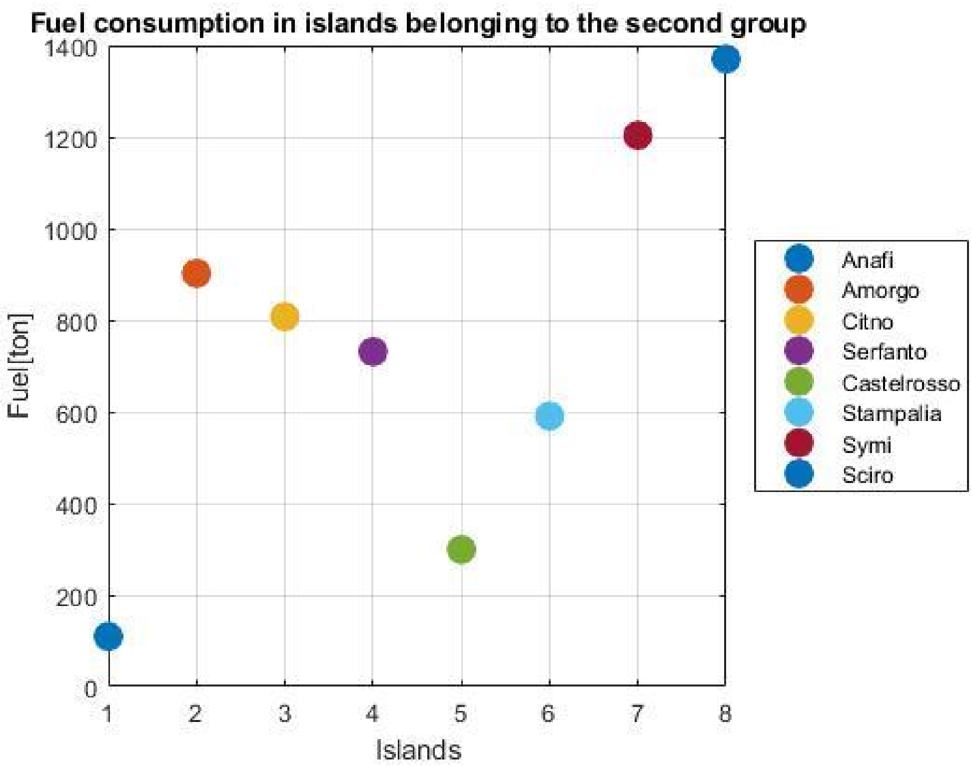

Figure 67: Fuel consumption for islands belonging to the second group

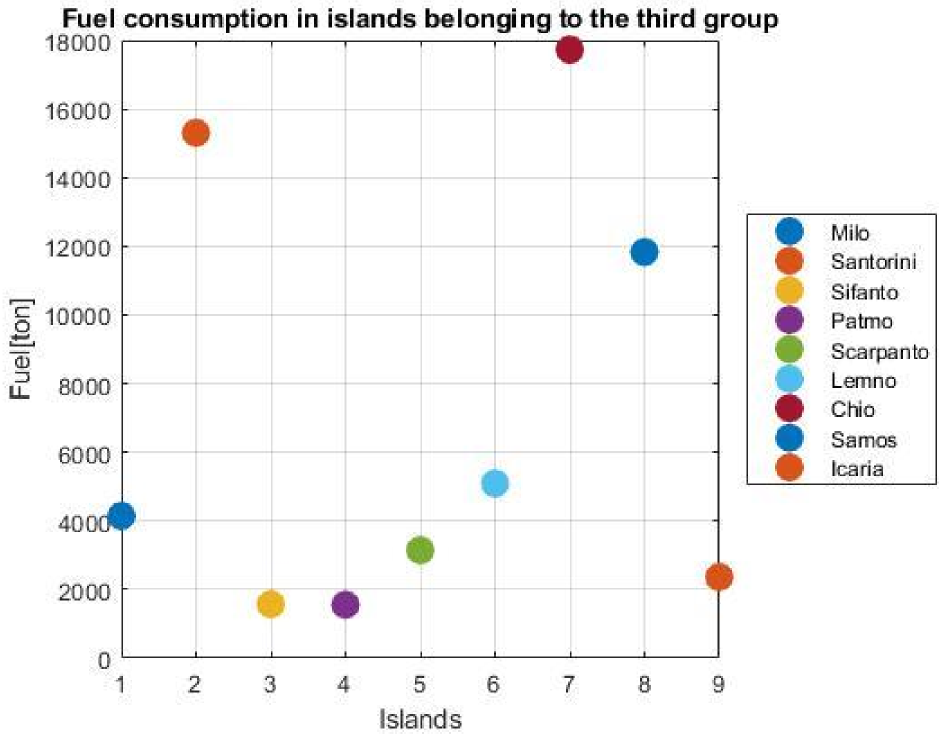

Figure 68: Fuel consumption for islands belonging to the third group

The results show an avoided fuel consumption of 61,25 [tons] for Agathonisi, 1203,45 [tons] for Symi and 15305,31 [tons] for Santorini. Since this consumption is calculated through equation 16, from the annual energy consumption of the other islands (see section 2), values will be obtained that are directly proportional to the values of the latter data. However, the most significant result remains the potential consumption avoided by all the islands not interconnected to the grid, summarized in the following table:

	1st Group	2nd Group	3rd Group	Total
Fuel Consumption [ton]	463,35	6013,65	62728,31	69205,31

Table 40: Fuel Consuption for feasable islands

To the 69,2 thousand tons avoided per year must also be added the possible future savings associated with the islands belonging to the fourth group, for which consumption is much higher.

6.2 EMISSIONS

The emissions analysis includes two parts. The first reports the analysis on the lack of CO_2 released into the atmosphere, a fundamental and essential data for an analysis of sustainability as it is responsible for the greenhouse effect, the second reports an analysis on the substances belonging to the group of acidifiers, responsible for acid rain. .

6.2.1 EQUIVALENT CO_2

Some gases present in the atmosphere, of natural and anthropogenic origin, absorb and emit infrared radiation at specific wavelengths, causing the phenomenon of the greenhouse effect. This includes carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFC), perfluorocarbons (PFC), sulfur hexafluoride (SF_6). Greenhouse gases allow solar radiation to pass through the atmosphere and hinder the passage to space of part of the infrared radiation coming from the Earth's surface, thus contributing to global warming. Each of these gases has its own specific heating potential. To calculate the overall greenhouse effect emissions, the quantities relating to the emissions of individual pollutants are converted into tons of CO_2 equivalent, obtained by multiplying the emissions of each gas by its own heating potential, Global warming potential (Gwp), expressed in relation to the potential of carbon dioxide heating. Through the report number 303 of 2019 provided by ISPRA (Higher Institute for Environmental Protection and Research) it is possible to obtain the CO_2 equivalent value per kWh produced by Greece and referred to the year 2017, equal to 535,4 [g CO_{2eq}/kWh] [17].

Multiplying the annual energy load by the related CO_{2eq} emission factor, the tons of carbon dioxide equivalent that the system would allow to avoid introducing into the environment are obtained:

$$CO_{2eq}\left[\frac{ton}{y}\right] = Load\left[\frac{MWh}{y}\right] * 535{,}4\left[\frac{g\ CO_{2eq}}{kWh}\right] * 10^{-3} \quad (19)$$

The following figures show the results for all the Greek islands not interconnected to the national electricity grid.

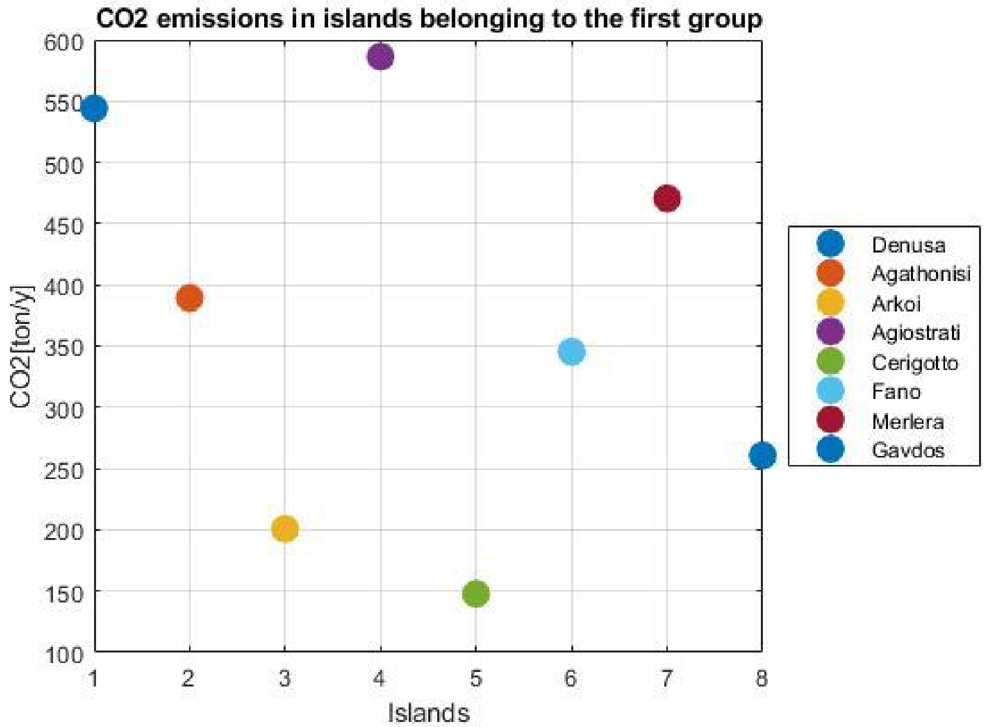

Figure 69: CO_2 emissions from islands belonging to the first group

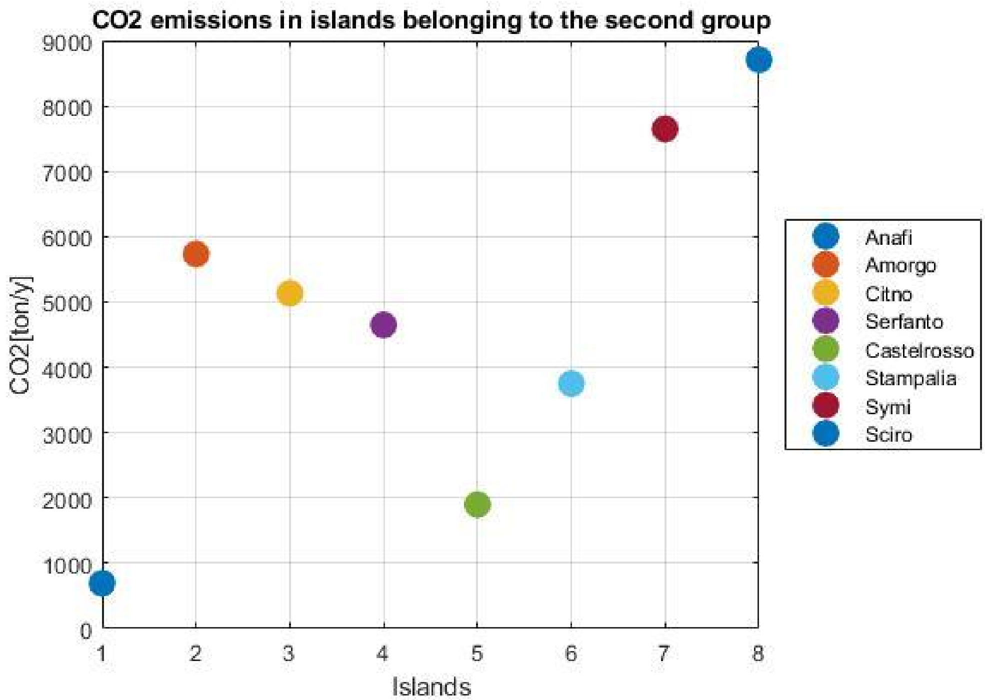

Figure 70: CO_2 emissions from islands belonging to the second group

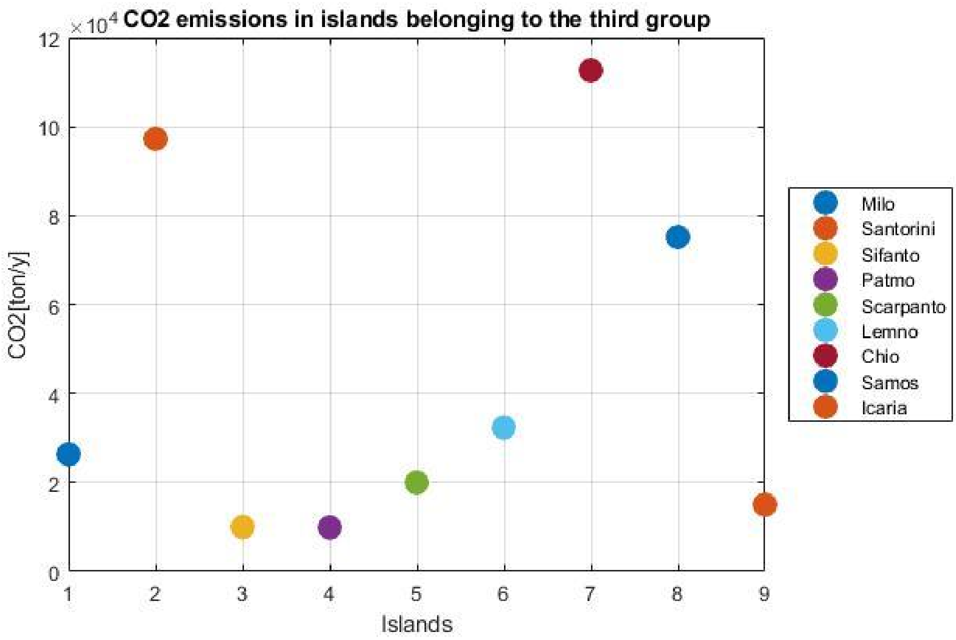

Figure 710: CO_2 emissions from islands belonging to the third group

The CO_2 equivalent emissions related to Agathonisi, Symi and Santorini are respectively 389,23 [ton/y], 7648,2 [ton/y] and 97268,26 [ton/y]. The Santorini's result, which is among the most energy-intensive islands in the Aegean Sea, suggests the benefits that the system would bring to the environment. Expanding the analysis to the rest of the islands, the total value of tons of CO_2 equivalent is extracted, produced by fossil fuels for the generation of electricity, not released into the atmosphere; a result that if it were also extended to the islands belonging to the fourth group it would lead to a turning point towards the affirmation of the energy transition.

	1st Group	2nd Group	3rd Group	Total
CO_2 emissions [ton/y]	2944,70	38217,92	398650,81	439813,43

Table 41: CO_2 Emissions for feasible islands

6.2.2 ACIDIFICATION

The main atmospheric emissions that contribute to the formation of acid rain concern nitrogen oxides (NOx), sulfur oxides (SOx) and ammonia (NH_3). Similarly to the case of the greenhouse effect, to aggregate the emissions of the various pollutants that contribute to the acidification phenomenon, the different potential of each of them is taken into account (Potential acid equivalent-Pae), thus reaching a common unit of measurement. The measurement in tons of equivalent acid potential was obtained once again from the report number 303 of 2019 provided by ISPRA [17], considering exclusively the components of Nox (355,67 [mg NOx/kWh]) and SOx (110,66 [mg SOx/kWh]) as they are clearly more significant than ammonia. By multiplying the coefficients by the respective energy loads and adding the results together, the values of equivalent acid potential released into the atmosphere by each island are obtained.

$$NO_x\left[\frac{kg}{y}\right] = LOAD\left[\frac{MWh}{y}\right] * 355{,}67\left[\frac{mg\ NO_x}{kWh}\right] * 10^{-3} \quad (20)$$

$$SO_x\left[\frac{kg}{y}\right] = LOAD\left[\frac{MWh}{y}\right] * 110{,}66\left[\frac{mg\ NO_x}{kWh}\right] * 10^{-3} \quad (21)$$

$$Pae\left[\frac{kg}{y}\right] = NO_x + SO_x \quad (22)$$

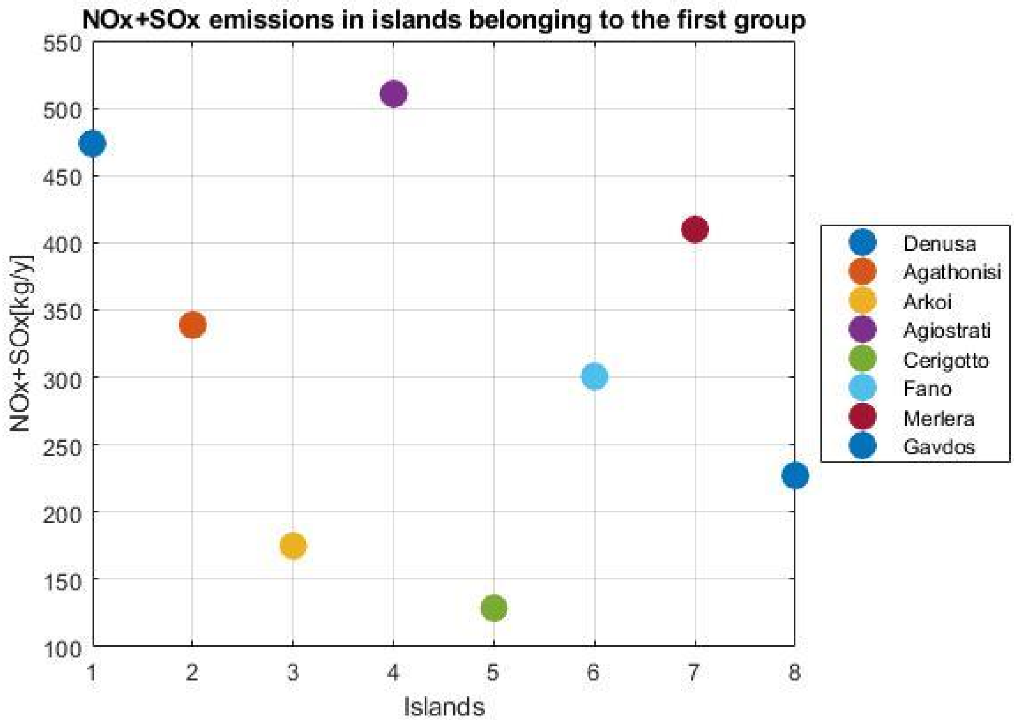

Figure 72: Pae emissions from islands belonging to the first group

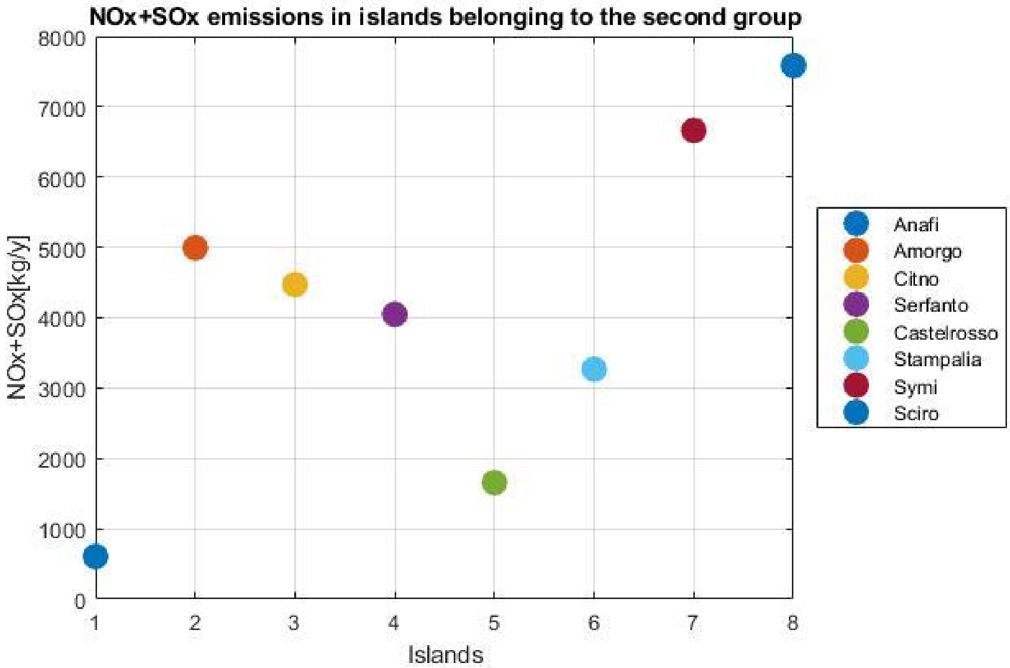

Figure 73: Pae emissions from islands belonging to the second group

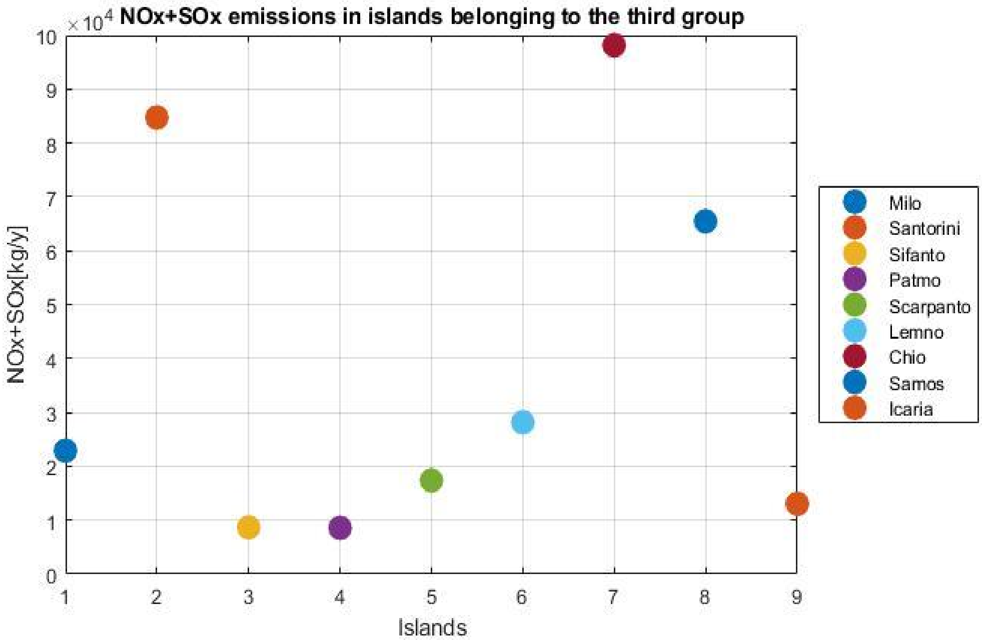

Figure 74: Pae emissions from islands belonging to the third group

The results of the 3 analyzed islands show significantly lower emission of equivalent acid potential compared with the previous CO_2 equivalent values (Agatonisi 339 [kg/y], Symi 6,66 [ton/y] and Santorini 84,72 [ton/y]). However, the projections on the total emissions of these substances into the environment, extended to all the islands, confirm the effectiveness and sustainability of the hybrid system, avoiding the release into the atmosphere of 382,85 tons per year.

	1st Group	2nd Group	3rd Group	Total
Pae emissions [ton/y]	2,34	33,29	347,22	382,85

Table 42: Pae Emissions for feasible islands

7 CONCLUSIONS

The energy transition represents the most important challenge that our generation and future ones will have to face in the coming decades. The continuous increase in population and the consequent increase in energy demand, has led to an unprecedented production of greenhouse gas emissions, inevitably affecting our planet. The goal of containing global warming, in parallel with the satisfaction of the energy load, can only be achieved through concrete and shared commitments worldwide, supported by the introduction of new innovative technologies. For too many years the energy sector has not been subject to reforms and interventions necessary to contain consumption. To cope with the consequences of climate change, in considerable times, it is necessary to act collectively, with short and long-term environmental policies that aim to reduce waste, optimizing the use of energy resources and introducing new technologies with high environmental compatibility.

The aim of the work is to estimate the potential of Power-to-Power systems for the remote islands not interconnected to the national electricity grid of Greece, through the analysis of a hybrid system including solar panels, wind turbines, fuel cells and batteries. The acquired data highlighted a strong need for intervention for the realities characterized by a low number of inhabitants and a consequent low consumption, bound to pay enormous prices to import fuel and generate electricity. The annual performance analyzes for the proposed system showed the potential of the plant, demonstrating its ability to meet the required loads without exploiting any fossil resources. Given the high energy generation prices, within an optimization algorithm, used to derive the sizes of the various system components, the search for the lowest possible LCOE was set as an objective function, with results that brought out the preference to use hydrogen as storage technology. The economic analysis subsequently highlighted the possibility of installing the plant, at current market prices, only in islands with a not very high energy load, consequently limiting its field of applicability. However, the most evident results are those concerning emissions. From the calculation carried out on the pollutants emitted into the atmosphere, due to the use of diesel engines, the true potential of the system emerges, which has proved, as well as capable of replacing the now old energy stations, able to play a fundamental role in reducing atmospheric pollution.

I personally believe that the results obtained are of fundamental importance and that they can serve as a starting point for future studies. The analysis of the scenarios projected to 2030 clearly demonstrated the validity of the project, making the plant not only installable even in areas where it would currently be prohibitive, due to high costs, but even bringing it an economic benefit. The continuous search for technologically more and more advanced and efficient solutions will certainly lead to the expansion of the field of applicability of the proposed system, making it available also to realities that are much more energy-intensive than those analyzed. The new environmental and energy policies launched in Europe and worldwide will serve to incentivize investment in research and installation of systems based on renewable sources, increasingly going to replace production from fossil sources in a more economical and convenient way, narrowing the gap that separates us from the energy transition. Numerous climate studies conducted by the United Nation Organization (ONU) and other research groups, in particular by the MCC (Mercator Research Institute on Global Commons and Climate Change), have led to estimate zero time as January 1, 2028 , a moment in which, due to the carbon that we continue to put into the atmosphere, we will have missed the goal of containing the increase in average temperatures by 1,5 [°C] compared to the pre-industrial era, the most virtuous target signed in 2015 Paris Climate Agreement. This is the time we have available to prevent the climate crisis from becoming irreversible. We need to become aware of the direction we are moving in and take a decisive step towards a sustainable and zero-impact energy generation, to safeguard the survival of our planet and humanity itself.

8 ACKNOWLEDGMENTS

The biggest thanks certainly go to my parents and my family, who through enormous moral and economic support have never made me lack for anything, eliminating the distance that still separates us.

Special thanks to professor Santarelli and to the PhD students Marocco and Ferrero, supervisor and co-supervisors of the work, for showing me great professionalism, competence and availability over the past months.

I thank my girlfriend Sofia enormously, for always having been able to count on her and for always making me feel her presence and her support even when almost 1200 [km] separated us.

Thanks to my colleagues, companions of joys and sorrows, for sharing with me every day of this journey.

Thanks certainly go to my friends, whether they are in Pozzallo, Turin, or other parts of Italy, which I consider like a second family, for their daily presence.

Thanks to all of you, this work is also your merit.

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