Department of Mechanical and Aerospace Engineering

Implementation of Hybrid Energy Systems for an off-grid island in Greece

Author: Marinos Mavroulis

Supervisor: Daniel Costola

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Copyright Declaration

Signed: *Marinos Mavroulis* Date: 24/08/2018

ABSTRACT

The energy requirements of the off-grid islands in Greece are covered by oil-based power plants. Their use can be heavily decreased by the utilization of renewable energy sources. This paper investigates various hybrid energy solutions for a non-connected with the mainland Greek island.

Greece is a country with a high potential for wind and solar energy but their exploitation is still remaining in relatively low levels. Consequently, this thesis is mainly focused on wind and solar power and on the benefits of Hybrid Energy Systems. In addition, the significance of storage options in those systems is described. Donousa was chosen as a case study of this project because it represents a typical off-grid island of the Aegean Sea with extensive periods of sunshine, high rates of wind speed and high proportions of tourists during summer.

The modelling tool that was selected in order to evaluate the implementation of different energy scenarios is HOMER. The electrical demand profile of the island obtained from a previous project. After the input of the necessary parameters the software program 4 different energy systems were examined: A system of photovoltaics and diesel generator, a system of wind turbines and diesel generator, a system of photovoltaics, wind turbines and diesel generator and a pure renewable energy system with photovoltaics and wind turbines. All those systems were simulated for 3 different types of batteries in order to examine which is the most suitable. These are: Lead-Acid, Lithium-Ion and Vanadium Flow. Furthermore, the initial pure diesel generator system of Donousa was also simulated.

After the result analysis, it was revealed that for every type of battery the system with the lowest cost and cost of electricity is the combination of photovoltaics, wind turbines and diesel generator. Among those systems, the configuration with the lead-acid batteries was found to be the most cost-effective solution. Moreover, the diesel engine produces only 2.25% per year of the total electricity produced by this system and subsequently the CO_2 emissions were heavily decreased by 96.5%. Concerning the total net present cost and the cost of electricity of this scenario, it can be seen a notable reduction by 71.1% and 70.9% respectively, comparing to the initial system.

However, there are some uncertainties regarding the changes in the cost of the components during the project lifetime, which should be evaluated carefully in order to achieve more precise cost estimation. A sensitivity analysis showed that alternations in

diesel price can cause fluctuations up to 1.6% to the total cost of the system despite the fact that the diesel engine has a minimal contribution to its overall electrical energy production.

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LIST OF SIMBOLS

n- Overall efficiency of a diesel power generator (%)

n_i- Energy efficiency of photovoltaics (%)

V- Voltage (Volt)

I- Current (A)

v- Wind velocity (m/s)

P_{eff}- Effective power output of wind turbine (W)

C_p- Power coefficient (%)

ρ- air density (kg/m^3)

ACRONYMS

HES- Hybrid Energy System

RES- Renewable Energy Sources

NPC- Net Present Cost

COE- Cost of Electricity

CRF- Capital Recovery Factor

CO_2- Carbon Dioxide

PVs- Photovoltaics

WT- Wind Turbine

Li-Ion- Lithium Ion

RF- Renewable Fraction

EE- Excess Electricity

NiCd- Nickel Cadmium

NiMH- Nickel-metal Hydride

VRB- Vanadium Redox Flow Batteries

CAES- Compressed Air Energy Storage

AC- Alternating Current

DC- Direct Current

1 INTRODUCTION

1.1 Problem definition - background

The technological and industrial development of the last 2 centuries has increased global energy consumption, and has created concerns about the availability of fossil fuels in the future (Matthew J.Burke, 2018). Simultaneously, very significant ecological and environmental problems have arisen due to the unreasonable use of conventional fuels (Ghouali Yassine Zakarya, 2015), as well as serious accidents that have called into question the widespread use of nuclear energy (William J.Nuttall, 2017). Furthermore, the utilization of fossil fuels results to the depletion of their sources (Creina Day, 2017) and for those reasons an increasing interest in the integration of renewable energy sources, have been developed. Many attempts and studies have been made in order to optimize stand-alone Renewable Energy Systems from both financial and energy point of view (Atefeh Behzadi Forough, 2018). A major issue is the choice of the optimal parameters which should be set up for energy cover in blend with the most efficient economical solution (G.N. Prodromidis, 2011).

Another problem appears to be the high prices of the cost for the constant supply of the electrical demand, mainly in remote regions such as islands (Jiahong Liu, 2017). Especially, the non-interconnected islands with the national grid use autonomous power stations and depend on purchases of oil-fuel (Maria Chalakatevaki, 2017). The 1/6 of land's surface at a worldwide scale is consisting by islands which host around 10% of earth's population (Baldacchino, 2008). However many small islands regions throughout the world are dealing with energy infrastructure problems which affect the quality of life of the residents (Konstantinos D.Patlitzianas, 2012) and in many occasions policies about sustainable development of the energy sector in those regions are not clear (Tzanes, 2017). On the other hand, the electricity grids in offshore islands are suitable for the implementation of renewable energy systems because of the weathers conditions and the high price of the fuel cost (Kornelis Blok, 2018). Thus, several countries around the world adopt and implement many island projects related to renewable energy generation (Jhih-Hao Lin, 2016). The advantages of its efficient exploitation do not only contain a decrease in the carbon dioxide emissions on a local scale, but also a decrease in the reliance on fossil fuels and in energy infrastructure investments alongside with higher competitiveness and profitability for consumers (Stilianos Tampakis, 2017) (Sandrine Selosse, 2018).

Among all Mediterranean nations, the country with the most wide coastline (around 15000km), is Greece (J.K. Kaldellis, 2012). It has more than 3000 islands accounting for 20% of its land area and most of those them are located in the East side of the country in the Aegean Sea (Figure 1) (Union, 2014). The Greek energy sector comprises of 2 subsystems, the principal interconnected electrical grid that supplies the demand of the mainland and the insular power stations of Aegean islands (N.Georgiou, 2016). Specifically, there are 32 islands which are not-interconnected to the mainland's electricity grid (Georgios N. Psarros, 2018). Furthermore, in those islands the electricity production is mainly based on stand-alone oil power stations which use heavy fuel oil such as mazut or light fuel oil such as diesel (Eleni Strantzali, 2017). Despite Greece's intentions to connect most of the Aegean islands with the national grid by 2030, due to the financial crisis of the country and its current economic situation, this aim seems to be very optimistic (Eleni Zafeiratou, 2015).

Figure 1: Map of Greek islands (J.K. Kaldellis, 2012)

Until today, those islands have not being connected with the electrical power system of the mainland due to economical obstacles, since the interconnections require a high capital investment, and because of technological, governmental and environmental limitations (Oikonomou EK, 2009). In result, they face problems due to high-cost electricity supply and blackouts during periods of high energy consumption (mostly the summer period due to the rates of tourism) (M. Bertsiou, 2018). In some cases, the electricity generation cost exceeds even 700€/MWh. (PPC, 2015) Moreover, the constant rise of the energy demand increases also the fuel's imports and the dependency of the islands from fossil fuels and making them highly vulnerable to fluctuations of fuel price (Evangelos Moschos, 2017). Thus, environmental pollution occurs due to their emissions and the cost of electricity production is increasing. At the same time, all these facts highlight the urgency and the necessity of the exploitation of Renewable Energy Sources in Greek islands, in order to deal efficiently with these issues and accomplish their electricity independency (John A.Paravantis, 2018).

The energy policy of Greece is based on lignite (Panagiotis Drosatos, 2016). As a country of the EU, Greece participates in the National Action Plan, which aims to achieve a 20% of the overall energy consumption coming from renewable energy sources by 2020 (H.D. Kambezidis, 2011) (Maria Frangou, 2018). According to the country's legislation plan, its specific objectives until 2020 are the increase of RES in the total energy consumption and electricity consumption, by 20% and 40% respectively (Eleni Zografidou, 2017). Furthermore, European nations agreed to a recent 2030 legislation plan on energy and climate, which requires no less than a 27% of renewable energy utilization (D'Adamo I, 2016). Additionally, Greece relies on electricity imports which come to 65.3% and is rated 8^{th} of the 27 nations of EU in accordance to its reliance on energy imports (Azam M., 2016). As it can be seen from the above the utilization of RES not only has financial and environmental benefits, but it's necessary for Greece, in order to achieve its overall energy goals and commitments towards the European Union (Dimitris Manolopoulos, 2016). Moreover, the country has high and exploitable energy potentials in the sector of Renewable Energy Sources and can notably increase their utilization (Koltsaklis NE, 2014).

Hybrid Energy Systems are being considered as an effective solution to these difficulties (P.Blechinger, 2016). Currently, for the majority of these islands there is no arrangement for interconnection with the mainland grid of Greece (despite some thoughts and intentions) and the constant increase of electricity consumption is to be covered by new oil-based power stations (Tzanes, 2017). Additionally, the climate of the Aegean Sea favors the exploitation of Renewable Energy Sources, with solar and wind power to be the most dominant form of energy generation due to the high wind and solar potential of the Aegean territory (G. Caralis, 2010) (J.K. Kaldellis, 2009). This is due to the fact that during the winter the wind speeds are very high and at the same time there is a high annual percentage of sunshine (especially in summer). Specifically the monthly wind speed range is between 6m/s and 15m/s, while the solar radiation is among 60kW/m^2 and 230kW/m^2 (E.D. Giannoulis, 2011). There are although some considerations and limitations that have so far delayed the installation of new HES in Greek Islands such as land–use barriers, the size of the regional power electricity systems and the extreme seasonal fluctuations of load demand (Georgiou P., 2011).

1.2 Aim and Objectives

The aim of this project is to analyse and evaluate which is the most suitable Hybrid Energy System for a non-interconnected to the mainland Greek island, from an environmental and financial point of view and in general to present the benefits of the utilization of HES in isolated regions which are not connected to the power grid. The main idea of the different combinations is that when the demand could not be covered by the installed renewable energy systems the diesel generator will produce the extra electricity needed.

The objectives of this project are:

- Acquire the data of the load profile of the off-grid island in Greece.
- Investigate the renewable energy potential of the island due to its geographical location and apply the most suitable combination of RES and storage options.
- Use the appropriate software tool in order to import the data of the energy demand of the island and simulate different energy systems.
- Propose the most cost-optimal hybrid energy system and run a sensitivity analysis in order to understand the impact of an uncertainty.
- Recommendation of a hybrid energy system that will reduce the CO_2 emissions of the diesel generator and the island's dependency of external sources and fuel imports.

1.3 Overview of methodology

The overall overview of methodology of this project is presented in Figure 2 below. Based on every section of this dissertation the most important steps have been highlighted.

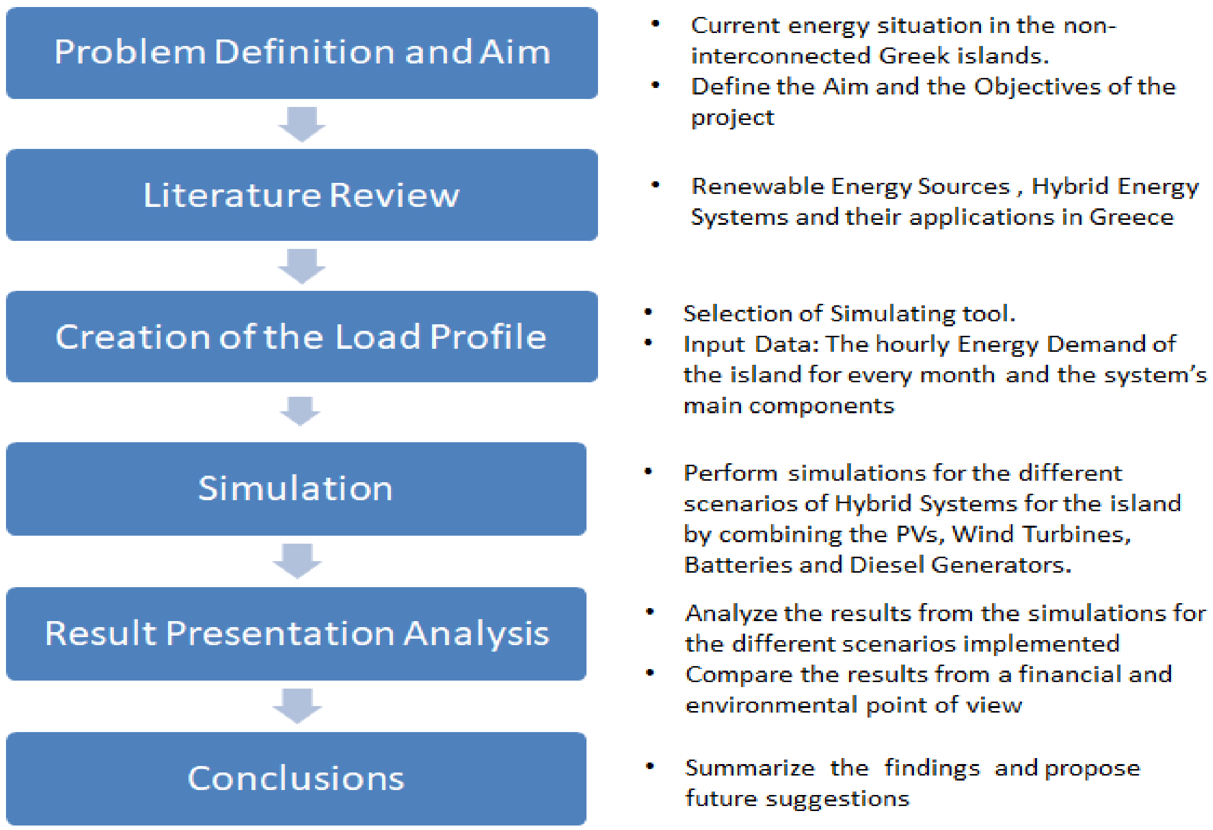

Figure 2: Overview of methodology

Specifically, the methodology of this project consists of some specific steps that need to be taken in order to achieve its aim and objectives. These are:

- Review the current energy situation in the off-grid islands in Greece, with special reference in the problems that occur from the utilization of fossil fuels as an energy source and possible solutions that can be applied.
- Investigate the hybrid renewable energy systems and their applications and inquire into the potential of exploitation of RES in Greece and its islands, mainly focusing on wind and solar power, as well as, various storage options.
- Select a suitable software tool and insert the data of the hourly electricity demand of the Greek island. Moreover, before the simulation process it is necessary to choose the technical components regarding the generation and storage.
- Create the model and examine various optimal hybrid energy scenarios by assessing their economics, energy performance and emissions.

- Analyse and compare the results of the simulations from a financial, energy and environmental point of view.
- Summarize the findings of this paper and recommend future suggestions.

1.4 Structure of the dissertation

This dissertation is structured in 5 sections, as follows:

Section 1 highlights the problem definition and its background and presents the aim and the objectives of the project, as well as, the methodology that will be followed in order to achieve this aim.

Section 2 presents the literature review which covers various aspects related to the topic of this project. Particularly, it illustrates information about renewable energy sources and their advantages, Hybrid Energy Systems and their application, as well as, the situation in Greece. Additionally, Wind and Solar power are the 2 notable forms of energy that will be analysed in this section alongside various storage options.

Section 3 includes the software tool that will be used and the characteristics of the case study of this thesis. It reveals the inputs made in the simulation part and explain us the parameters that will be applied in this model.

Section 4 outlines the results from the simulations. Specifically, for the selected combinations of the Hybrid Energy Systems that will be studied the results are presented and analysed from an environmental, financial and energy performance point of view.

Section 5 sums up the work of this project. The results and the conclusions are discussed and proposals for future work are provided.

2 LITERATURE REVIEW

In order to establish the significance of this project, it is essential to create a context with theoretical background that supports the aim of this dissertation. Initially in section 2.1, information about renewable energy sources and their applications are described, as well as, their current development in Greece. Furthermore, diesel generators and their characteristics are introduced and Hybrid Energy Systems are presented, alongside their advantages and their implementation in Greece.

Due to the fact that Greece and Greek islands have high wind and solar potential, in the next 2 sections (2.2, 2.3) details about these 2 forms of energy are analyzed. Attention is paid to their exploitation in order to produce electricity and the current situation of their installation and utilization in Greece and Greek islands is presented.

Finally, in section 2.4 the essence of storage is introduced. Additionally, the importance of its integration with renewable energy sources and its benefits is explained and various types of storage systems are illustrated. Special mention is made to batteries and their characteristics because they are one of the most-used storage devices in HES.

2.1 Renewable Energy and Hybrid Renewable Energy Systems

2.1.1 Description of Renewable Energy

In the last century, energy production was based on the burning of fossil fuels which accounts for more than 80% (Figure 3) of the total energy production worldwide (Agency, 2017). But their uncontrolled pumping has led to an imminent exhaustion of their inventories today. Perhaps the most significant drawback of conventional energy sources is the environmental impact of their exploitation by releasing greenhouse gases emissions (Sonali Goel, 2017). Furthermore, the fossil fuel sector experiences many adverse consequences due to factors regarding their price, storage and transportation (SK.A. Shezan, 2016). Nowadays, increasing environmental pollution affects the lives of every human being. World events such as the rise of global warming, the reducing rainfall, the reduction of water reserves and unexpected weather events are the visible results of energy activity and philosophy of previous years (Karna Dahal, 2018). Therefore, it is understandable that alternative solutions to energy production have to be considered since a reduction in demand is unlikely due to the new way of life of people. In addition, particular attention should be paid to the impact of the use of each energy source on the environment. Still, improving existing facilities and creating environmental policy is necessary.

Towards a sustainable future development, the necessity for detraction from conventional sources of energy and the effort to reduce pollution of the environment, lead to the use of RES, which largely solve the above issues (A. Mohammadi, 2016). Energy sources such as wind, solar and water are characterized as renewable since they are constantly renewed and are directly exploitable by humans. RES are now considered to be competitive for energy supply (Anjana Das, 2018). Greater production and extensive research in the field have led to decrease production costs and increase system performance of them. The application of renewable energy will contribute to the decarbonisation of the power sector, to the mitigation of climate change, to improvement of energy security, as well as to energy self-sufficiency and development of isolated areas (Bing Wang, 2018). Finally, new jobs will be created and environmentally friendly systems will replace polluting energy production methods.

Renewable Energy Sources contain many different forms of energy that can be produced from sources that are not exhausted or that can be rapidly replaced by biochemical processes of the earth. These are solar, wind, biomass, geothermal, hydropower, wave and tidal (N.L. Panwar, 2011). Moreover, despite their high capital cost of installation and their long pay-back periods more and more countries and governments in order to adopt more environmental-friendly policies and reduce the greenhouse gas emissions, advocate their utilization and exploitation by offering various subsidies and grants to customers (Jeayoon Kim, 2016).

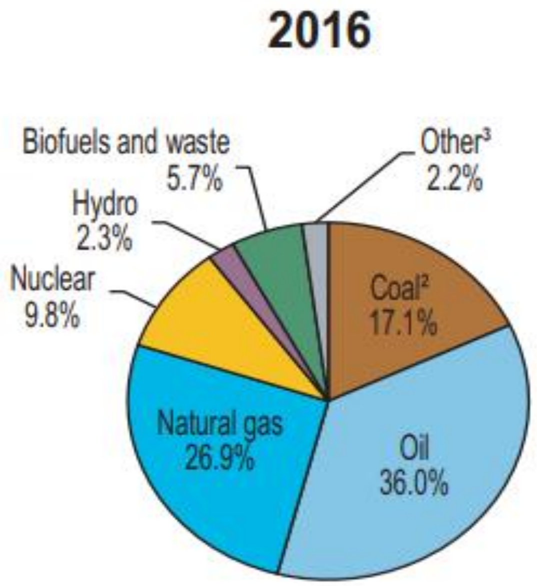

Figure 3: World energy supply by fuel 2016(Agency, 2017)

One of the most important sources of renewable energy is solar energy. It is electromagnetic radiation produced in the sun and absorbed by the atmosphere of the earth in the form of light and heat and it is practically inexhaustible. Regarding the utilization of solar energy, there are various systems which exploit this energy for heating or electricity requirements. The most noteworthy applications of them are the passive solar and active solar systems which use the irradiation of the sun, whereas PVs rely on the photovoltaic phenomenon and convert the solar radiation into electrical energy (Amir Shahsavari, 2018).

The other most notable and used form of renewable energy is Wind Energy. It can be defined as the energy produced by the wind. Its exploitation by humans is a practice that finds its roots in ancient times. Today, wind turbines are used to exploit wind power. Through their use the conversion of the wind's kinetic energy into electrical energy, is achieved. Firstly, the kinetic energy of the wind is transformed into mechanical energy and afterwards the mechanical energy is converted into electrical energy. The electricity generated by wind turbines can be consumed on site or exported to the grid (Nelson, 2014).

Biomass is defined as every type of organic matter that can be converted to energy. Specifically, biomass is associated with plant and forest remainders (such as firewood, branches, hay, olive trees and pits), wood waste, byproducts, animal waste (manure, waste), energy crops plants, as well as wastes and remainders from the food industry and agro-industry. It is mostly used for the generation of thermal energy and electricity. Moreover, it can also be used for the production of liquid biofuels (bioethanol, biodiesel, etc.). Many argue that it is a renewable energy source that may be acquired at low cost, reduces the energy dependence from fossil fuels and produces less CO_2 emissions them, under specific situations. Others support that biomass has seen constraint utilization as an energy source up to this point, since it has wide dispersion and seasonal production. Moreover, there is a difficulty in collecting, processing, transporting and storing it and requires more expensive facilities and equipment, compared to conventional energy sources (Bracmort, 2015).

Geothermal energy is defined as the natural thermal energy of the Earth that flows from its warm interior to the surface. It is considered as a virtually inexhaustible energy source (renewable), which is able with today's technological capabilities, to cover heating and cooling requirements, and in some cases also generates electricity. Geothermal energy provides a low cost of energy and it is considered environmental-friendly as it does not produce pollutant emissions. The usual temperature of the geothermal fluid or vapor is between 25 ° C to 360 ° C. In case of geothermal fluids having a high temperature (above 150 ° C), geothermal energy is mostly used for electrical energy production. The principal use of geothermal energy for thermal purposes worldwide is associated with greenhouse heating. It is still used in aquaculture, where aquatic organisms are bred, but also for district heating and heating of a set of buildings, settlements, villages or even cities (Mary H. Dickson, 2005).

Hydropower is one form of renewable energy that relies on exploiting and converting the dynamic and kinetic energy of the water of lake and water of the river respectively, into electrical energy. This conversion takes place in 2 stages. Initially, the conversion of the kinetic energy of water into mechanical energy takes place and afterwards through the generator the mechanical energy is transformed into electrical energy. By storing water in natural or artificial lakes, for a Hydroelectric Power Station, the saving Hydroelectric Energy is achieved. A significant advantage of a hydroelectric power station is that the predefined release of water and its extraction to hydro turbines results to a controlled electricity generation. Moreover, the high availability of water resources and their sufficient supply of the necessary rainfall, turn hydropower into a significant renewable energy source. Small scale hydroelectric units (micro-hydro) usually contain an unimportant amount of water collection and storage, and for this reason the building of sizable dams is not necessary. Consequently, the separation between small and large hydroelectric plants is usually happening. (Hermann-Josef Wagner, 2011).

A renewable energy source, which has so far been little used, is the energy of the sea, which covers 75% of the surface of Earth and can play a role of a massive energy tank. In addition, the surface of the sea can absorb a large quantity of solar and wind energy, which occur at sea in multiple forms, such as wave energy. Furthermore, many other types of energy in the marine environment are tidal energy and thermal potential between upper (warmer) and lower (colder) oceanic layers (ocean thermal energy). Nowadays, various wave and tidal power technologies have reached at such a technical stage that the mass exploitation of the sea to produce "clean" and "cheap" energy is now feasible (Gareth P.Harrison, 2005).

2.1.2 Renewable Energy in Greece

Energy demand in Greece has been steadily increasing since the 1950s and despite its current economic situation consumption levels remain high even today. For the last decades the country's main strategy has been the exploitation of lignite sources, which is the most dominant source of the country's electricity production (Figure 4), resulting in minimizing it cost of producing energy by making use of a polluting fuel (J.K.Kaldellis, 2014). The result of this policy was the creation of one poor energy balance and high ecological burden. In Greece, the history of RES development begins in 1985 with the first attempt to regulate power generation issues from alternative forms of energy. A substantial step towards the integration of RES into the Greek energy system took place in 1994 with the adoption of Law 2244/94, which contained favorable conditions for investors (Dimitris Manolopoulos, 2016).

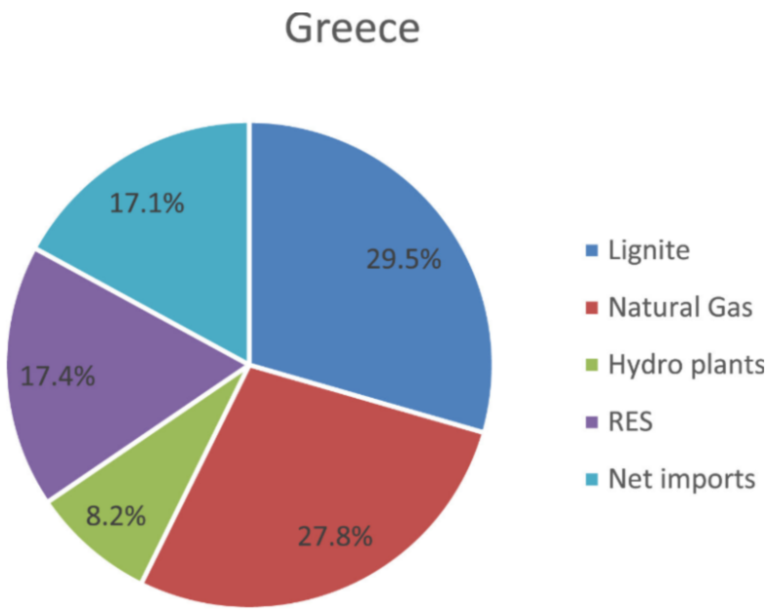

Figure 4: Electricity consumption in Greece, 2016 (LAGIE, 2017)

Greece is an ideal place for a wide use of RES (Garyfallos Arabatzis, 2017). The special morphological elements of its natural landscape in combination with its diverse climatic characteristics cover the necessary requirements for the technological growth of many applications of renewable energy sources (George E.Halkos, 2012). Its geographical location (latitude 38° N) ensures a great period of sunshine and high percentages of solar radiation and provides the possibility of an effective utilization of solar energy (G.C.Bakos, 2014). Also, the presence of many small but impetuous rivers, allows the use of available hydraulic power. Finally, the continental and island landscape offers natural passages in the transfer of massive air masses, shaping a considerable wind potential, especially in coastal and offshore areas (Papamanolis, 2015). Moreover the main generation of renewable energy increased by 39,711TJ, within a 10-year period between 2003 and 2013 (Papamanolis, 2015).

Solar power is increased in both non-interconnected islands as well as the rest of the country, due to its geographical location (Figure 5). Over the last years, significant efforts have been made to utilize this potential by both large producers with the installation of solar parks as well as PVs on rooftops (M.Karteris, 2013). It should be stressed that a major incentive is the selling price of the energy produced. The wind potential of Greece is a major source of energy because of its dynamics as it is highly concentrated in remote areas (Figure 6) (Ioannis Fyrippis, 2010). The Aegean islands, through their exploitation, can achieve significant detoxification from oil and with its prospect of their interconnection with the mainland, can act as exporters of energy to rest of the system (G. Caralis, 2010).

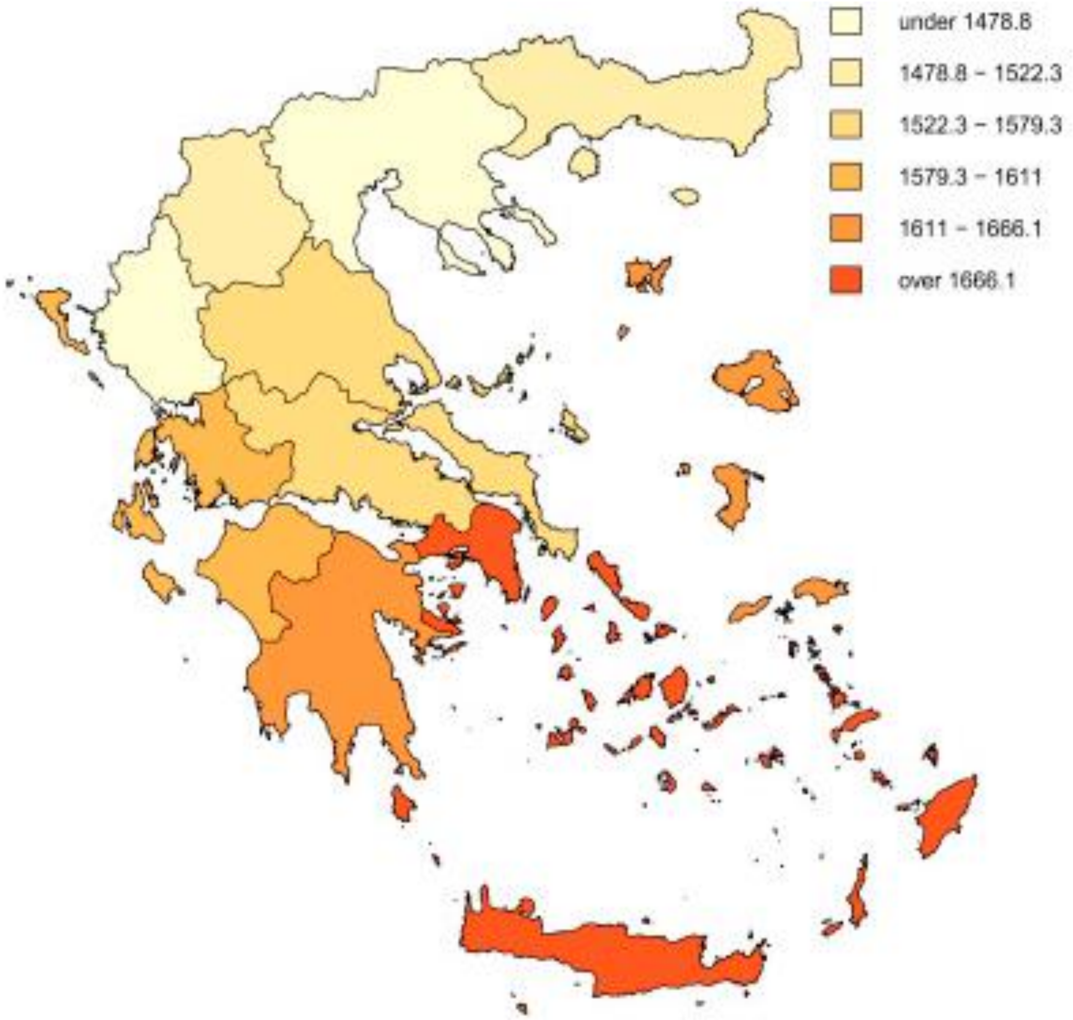

Figure 5: Solar irradiation of Greece (kWh/m^2) (Eleni Zografidou, 2017)

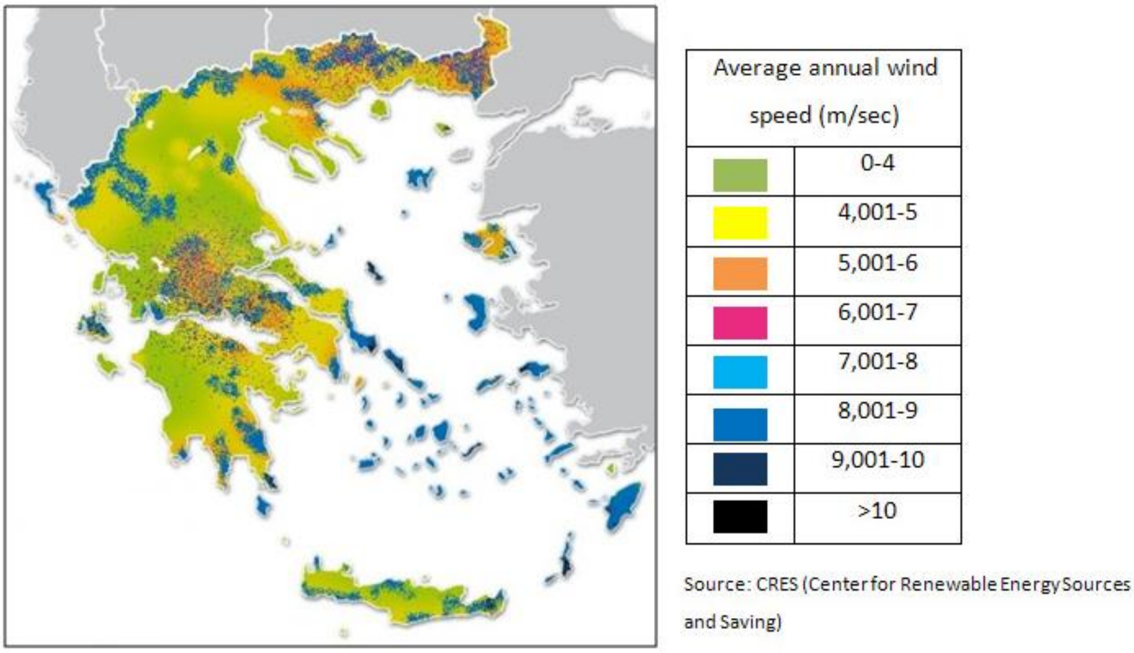

Figure 6: Wind potential in Greece (CRES, 2018)

2.1.3 Diesel Power Generators

The generator is a device that produces electricity and in some cases also thermal energy, consuming fuel. The generators have the characteristic of electricity supply according to demand, as well as, that of their rapid response to the constantly changing demand for electricity (A. Mohammed, 2015). In addition, when generators are combined with renewable energy units, they can provide back-up power in times when energy production of RES technologies is insufficient to meet demand. Generators include internal combustion engines, fuel cells, and micro-generators. The variety of fuels that can be used is great, and includes diesel, gasoline, natural gas, hydrogen, methanol, ethanol, propane, biodiesel, and biogas (Hasan Bayındır, 2017).

Diesel engines are vital parameters in micro-grid systems in order to in increase the network stability. Whereas, RES are constantly integrated into the electricity network, they are considered unreliable and intermittent due to the fact that they depend on seasonal and climate factors and can very regularly. In many islands the requirements of the energy demand of the residents are covered by diesel generators, which have the role of generating electricity and at the same time preserve the grid's reliability (Gökçek, 2018). Their mechanical components function in constant rotation (rpm) and constant air flow and subsequently require an extensive balance for its heat exchange demand. Despite the fact that developed diesel power generators have higher energy efficiency and power density, the genuine usage of their power output is usually lower than its ideal functioning point, because of the necessity to retain a considerable quantity of spinning reverse to cover the load inconstancy. The diesel engines must be able to of managing huge fluctuations in the electrical demand in the course of load regulations, which lead to high mechanical and heat pressures (Zamora, 2010).

The usage of diesel generators over its dynamic activity period, as far as a normal generator load factor, is usually under 70% of the rated capacity in accordance with the horsepower of the complementary motor unit. The sense of the demand profiles and surge current of the demand loads contribute to demand variability and they are the principle factors that are taken into consideration for the design of a generator unit (Tan Hang Kiang, 2017). Typically, diesel engines are estimated bigger to cater for short period of time of high power request such as the motor beginning currents, which is not perfect, as the financing in real estate and stability of the plan likewise developed accordingly. With the appropriate design, this 70% rated capacity rated capacity maximum limit of the loading, is considered as the full load of the engine. Due to high untapped supply, the diesel engine is underutilized, with around 20% to 30% of power capacity that is put aside for the primary load beginning phase, results to higher pay-back cost (Tan Hang Kiang, 2017).

Nowadays, the most common source of power supply to a Hybrid Energy System is the diesel generator, which consists of an electric alternating current generator driven by an internal combustion engine following the Diesel cycle. The fuel used is usually oil (diesel), and diesel particle sizes vary between a few kW and 1 MW. For very small sizes of diesel generators (below 25 kW), gasoline or propane combustion engines are a widespread solution. Micro-generators have been commercially available in recent years and their sizes range from 25 kW to 250 kW. Fuel cells are a completely different technology that directly transforms the chemical energy of the fuel into electrical energy, and is expected to be widely used in the years to come.

In a Hybrid Energy System, when the demand cannot be covered by the renewable energy systems or by the storage units (because of state of charge) then the installed diesel power generator covers it (A. Mohammed, 2015). The nature and the type of the load define the appropriate diesel engine that will be used. In order to calculate the rated capacity of the diesel engine 2 scenarios must be examined:

a) The rated capacity of the diesel engine must be leastwise equivalent to the maximum price of the load, when the engine is directly connected to the load (M.K.Deshmukh, 2008).

b) When the storage units are charged through the diesel engine, the engine generates a current that should not be higher than $C_{Ah}/5$ A. The current C_{Ah} is defined as the capacity of the battery (M.K.Deshmukh, 2008).

A diesel power generator has an overall efficiency:

$n = n_{\text{brake thermal}} \times n_{\text{engine}}$ (Nag, 2001).	(2.1)

$n_{\text{brake thermal}}$ is defined as the brake thermal efficiency of the diesel engine and n_{engine} as the efficiency of the generator. Under normal circumstances diesel generators are simulated in order to attain the necessary autonomy. Moreover, when there is no peak demand the diesel generators can be used as battery chargers (Gökçek, 2018). The consumption of the fuel of a diesel engine can be calculated by the following equation:

$FC_{DG} = F_o \times P_G + F_1 \times P_R$,	(2.2)

where P_G is the output power and P_R the rated output of the diesel generator. F_0 and F_1 are defined as the intercept coefficient and the slope of the fuel curve, respectively. The typical values of these F_0 and F_1 are 0.246 L/kWh and 0.08145 L/kWh, respectively (N.M. Isa, 2016).

A typical diesel generator and its main components can be seen in Figure 7 below.

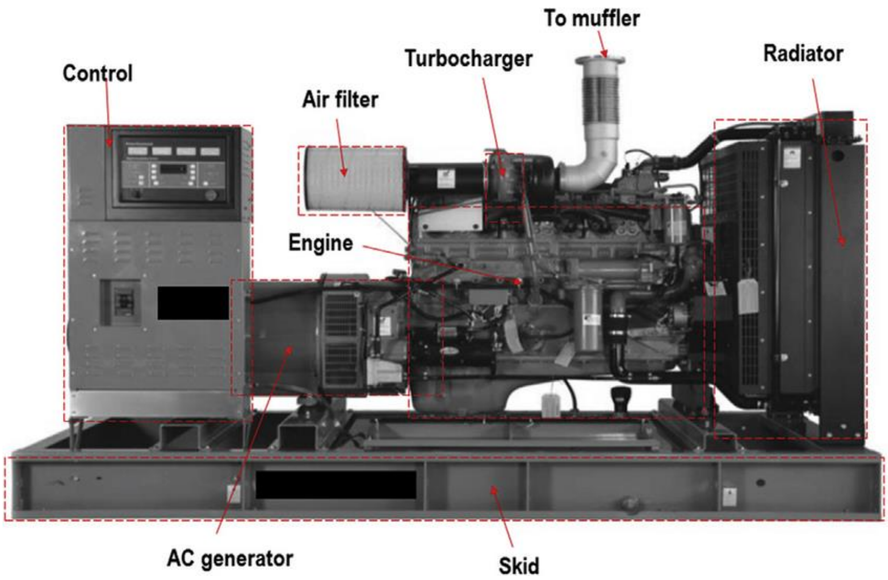

Figure 7: A typical diesel engine and its main components (Kelly Benton, 2017)

2.1.4 Hybrid Energy Systems

Energy dependence on fossil fuels for electricity generation, such as oil and gas brings to the surface issues such as their expected exhaustion and issues related to their extraction and exploitation. In addition, the burning of fossil fuels is the main cause behind the disruption of ecological balance (Peltovuori, 2017). Due to those key factors RES has gained the interest of all research and development studies. The 2 main technologies used for mass production and distribution of electricity are solar and wind. The stochastic nature of many forms of RES raises some techno-economic and functional constraints when using them to meet energy needs (Anastasia Ioannou, 2017). For example, the use of solar energy requires the use of storage units due to fluctuations in its availability. The same applies to wind power. These have led to the development of hybrid energy generation systems which are generally defined as systems where multiple energy conversion devices (electric generators of different technology for in-use fuel) are used to produce energy (T.M.Tawfik, 2018). A hybrid system may include a conventional power plant combined with at least one form of renewable energy source, storage devices, control systems and a load management system (M.J. Khan, 2005). In this sense, hybrid systems can be considered as an alternative solution to conventional systems, which are mainly rely on the production of energy from fossil fuels.

Non-interconnected renewable energy systems cover the demand for energy directly without the use of large transmission lines (Y.S.Mohammed, 2017). A hybrid energy system combines different but complementary RES-based energy systems as well as renewable and non-generating energy sources (Figure 8). Typically, hybrid systems include two or more RES combined with conventional power generation technologies, such as diesel generators (Lanre Olatomiwa, 2016). If the selection of renewable energy sources occurs properly and suitably for each topographical area, the requirement for fossil fuels will be heavily decreased. Therefore, this will lead to a more sustainable power generation, particularly in nations that depend on the utilization of fossil fuels (M.S. Ismail, 2013). The right combination of RES with conventional sources can ameliorate the credibility of the electrical grid, mainly under hard environmental circumstances and also decrease the number of barriers of RES and open markets for investments (S. Mekhilef, 2013).

In order to design and install successfully a hybrid energy system, there are many parameters that need to be taken into consideration. Initially, the national policy to promote hybrid power generation systems and more generally to promote RES, are necessary for its implementation (Michael Mutingi, 2017). Other notable factors are the load elements (daily kWh, peak demand) and the location characteristics of the installed hybrid energy system, as well as, the availability and exploitation of RES capabilities (M.S. Ismail, 2013). Furthermore, parameters such as the rate of penetration of RES technology into the hybrid system, its reliability and stability and the cost of its installation, operation and maintenance are also important and must be evaluated.

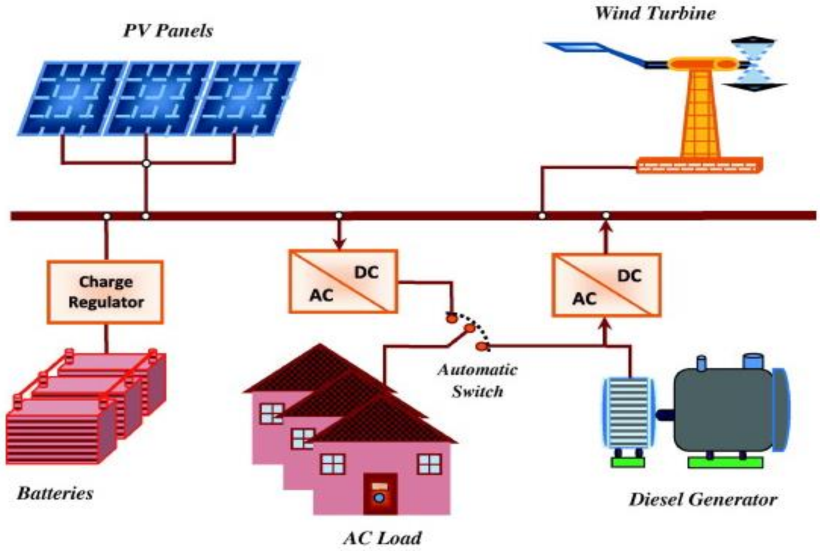

Figure 8: Wind-PV-Diesel system with storage (Abdelhamid Kaabeche, 2014)

2.1.5 Advantages of Hybrid Energy Systems and their applications in Greece

The implementation of standalone renewable energy sources can be viewed as unreliable because of the random nature of their resources and their related high expenses (Production, 2018). Hybrid systems are designed to optimize the use of the current power generation technology (such as wind turbines, photovoltaics, etc.) and provide energy for network absorption. Thus, they can be developed as stand-alone and independent systems or join existing oil-based thermal units, after the necessary interventions in the existing system (Jaesung Jung, 2017). They are usually installed in areas, where their connection to the grid and the transport of fuel are considered non-economic choices and provide the possibility of future networking (Yashwant Sawle, 2018). Moreover, fuel-powered energy systems operate at the lowest possible consumption because it is expected to generate energy from it only in times of high energy demand or the renewable energy source is not available (M.K.Deshmukh, 2008).

Another benefit of the implementation of HREs, as regards the speed of installation of technologies, is the relative stability of the cost of electricity generation and the use of environmentally friendly renewable energy sources (Kamal Anoune, 2018). HES have the potential to mitigate energy quality problems and generate high-quality, more stable and reliable power (P.G. Arul, 2015). Furthermore, despite the fact that the initial cost of installing wind and solar energy systems is higher than the oil-fuel power generator of similar size, the maintenance and operating costs are lower than those for the oil-fuel power generator. Moreover, the size of the storage units that are part of the hybrid system can be slightly decreased, due to the fact that there is less dependence on one individual power source (C.S. Supriya, 2011).

The interconnected with the grid hybrid power systems can be installed either for energy generation or as support systems in the event of a power cut, or produce energy at the peak hours when the demand is high (M.Edwin, 2018). These systems include RES units that are either directly interconnected to the grid or store their energy on batteries for use when needed (Sammy Houssain, 2018). Typically, factors influencing this are the price of kWh produced from each form of RES and the load to be covered when deemed necessary. Such small-scale systems are now widely used in developing countries, where rapid increase in demand often causes network instability problems that sometimes can lead to its collapse (Faizan A.Khan, 2018).

A notable difference between a stand-alone hybrid system and a hybrid system connected to the grid is that the stand-alone must be able to provide all the energy required at any time or to cut off a load when this is not feasible. In addition, it must have the ability to adjust the frequency and reactive power output to adjust the grid voltage. When electricity from the system's RES units exceeds the load, the excess energy must be stored or disposed of in a way that will not cause instability in the system (Sammy Houssain, 2018). Autonomous networks are strongly affected by the extra load or the generator connection. For the reasons mentioned above, most autonomous systems include power storage devices and load management and control systems (Wei Zhou, 2010).

In remote and rural regions and especially, in the non-interconnected islands of the Aegean Sea in Greece presented in Figure 9, where many consumers don’t have a direct and secured energy supply they rely on diesel power generators in order to cover their energy needs (John Kaldellis, 2012). Additionally, attempts have been made to implement HES that combine renewable energy sources with the existing conventional and the benefits for the islands are obvious. They acquire an important electricity supply for summer and winter periods, they avoid blackouts, increase their energy security and they reduce the CO_2 emissions (Tzanes, 2017). One of the first hybrid Wind-diesel-generator system with batteries that were created in Greece, were on the island of Kythnos, an island with high-cost electricity generation from diesel generators and a sufficient wind potential (Kaldelis, 2010).

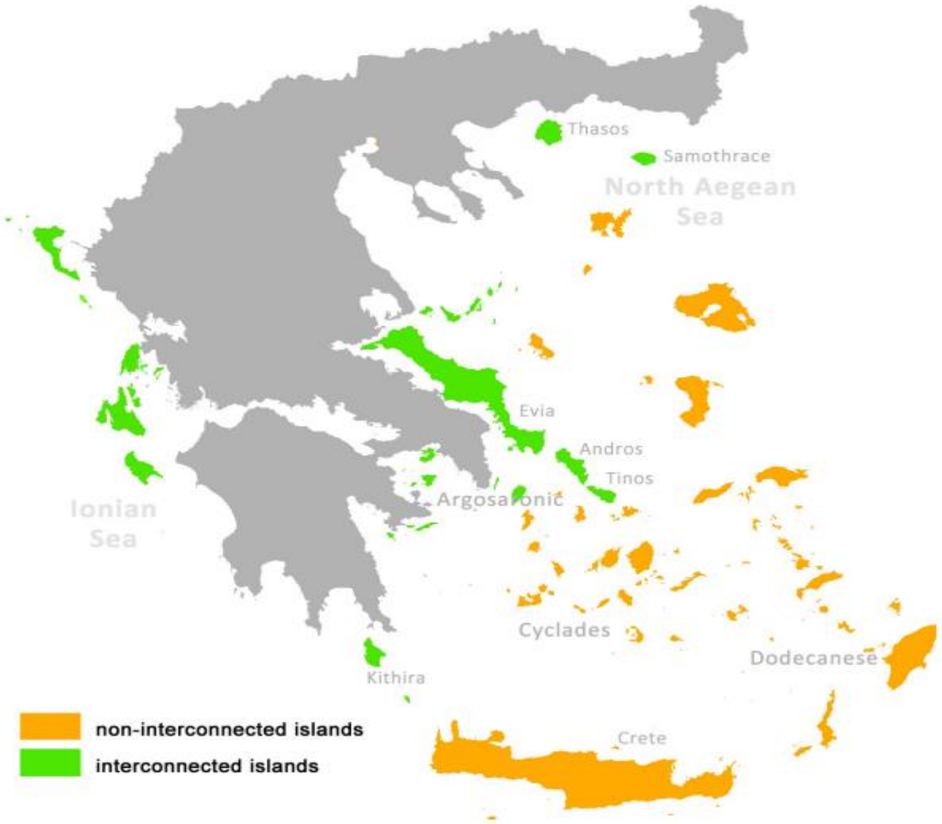

Figure 9: Connected and not-interconnected islands of Greece (Maria Panagiotidou, 2016)

Applications of Hybrid Energy Systems can also be found in the monasteries of Mount Athos where the isolated location of the mountain makes it unprofitable to connect the monasteries to the grid. Some of them have sufficient power supply and small-scale hydroelectric stations and photovoltaic systems have been installed. The main goal of this action was to significantly reduce the generator's operating time, resulting in significant fuel savings (with corresponding environmental benefits) as the replacement of diesel fuel from photovoltaic and hydro power (National Observatory of Athens, 2017).

2.2 Solar Energy

Solar energy is clean, inexhaustible and renewable. The exploitation of solar energy is quite widespread, mainly with applications of photovoltaic systems (PVs). Photovoltaic systems are based on the photovoltaic phenomenon, which is the direct conversion of solar radiation into electricity, using the technology of semiconductor materials that are activated in the spectrum of sunlight. Such systems are characterized as solar collectors and their operation is environmentally friendly, with a life span of around 25 years (Amir Shahsavari, 2018).

2.2.1 Operation of PVs

The structure and operation of PVs are based on semiconductors, which are coupled to negative and positive pairs (p-n) to form large-area electro-diodes. The correct construction of the electro-diode is a basic requirement for the successful operation of the photovoltaic cell as a semiconductor (Tsakalakos, 2010).

The cells are connected to each other in groups, constituting photovoltaic panels. With serial connection an increase in voltage is achieved, while the power of the panel is equal to the power of the cell. On the other hand, with the parallel connection the power of the panel is the sum of the power of the cells, while the current voltage equals the voltage of one cell (Stuart R.Wenham, 2011). Depending on the needs, it is possible to apply different combinations of the two types of connection. The size and shape of the panel depends on various parameters, such as its location and the way of its installation. A photovoltaic system consists of photovoltaic panel arrays with their metal bases, as well as inverters that convert the direct current into alternating current (A.Lynn, 2010).

In order photovoltaic systems to operate successfully over an expected life span, research is required in all aspects. Temperature and solar radiation are the two key factors that affect the performance of photovoltaic systems. Other environmental factors such as air, rain, cloud cover and solar spectrum distribution, affect the temperature below which the systems work, as well as, the expected incident solar radiation (M.M.Fouad, 2017).

Specifically, the factors that affect their efficiency are:

- The solar radiation: Increased solar radiation results to higher electricity generation and thus greater power output (M.M.Fouad, 2017).
- Temperature: High temperatures have a negative effect on converting solar energy to electricity, as they reduce performance and maximum power. The

operating temperature of the PV system depends primarily on the location of the installation. However, it is possible to install a cooling mechanism in order to improve the system's efficiency (John K.Kaldellis, 2014).

- Wind speed and direction: Large wind speeds lead to lower operating temperatures of the photovoltaic panel (John K.Kaldellis, 2014).
- Aging: Over time, there is a gradual decline in the amount of electrical power generated, which is estimated to be about 1-2% per year.
- The shading: The shading of photovoltaics usually by intense vegetation and dust has a negative effect on their performance (Xiang Zhang, 2018).
- The Soiling: The soiling of PV panels from dust accumulation can decrease the power output of the photovoltaic panels (Arash Sayyah, 2014).
- Photovoltaic system losses: In order to design properly a photovoltaic system, attention must be paid on the electrical losses in the conductors connecting photovoltaic panels to the arrays and their connections to other parts of the system, such as protection and control devices, accumulators, inverters, etc. Therefore, during the calculation of the required surface area of a PV system, provision should be made depending on the case to cover all such losses that may be around 30% of the generated electricity or more (Changwoon Hana, 2018).

2.2.2 PVs Installation

During the installation of PVs and according to the application requirements considered, the panels can be freely placed on the ground, on buildings or other structures and even used as structural elements and roofing materials.

Under circumstances of remote power generation, photovoltaic modules are interconnected and supported by metal modules. In particular, these metal frames in their simplest form, are immovable and fixed to the ground by various methods. The photovoltaic panels are mounted on them and connected to each other depending on the application. Furthermore, in many photovoltaic systems there are 2-3 levels of slope relative to the horizontal plane to maximize solar radiation absorption in different months and hours of the day (Tsakalakos, 2010). More complicated is the one-way installation to monitor the course of the sun. This axis may be either in the direction of the horizontal plane, so that the angle of installation in this regard varies daily with the day or in the direction of the azimuth (to the south), so as to change the position of the photovoltaic by following the daily motion of the sun (Mohand Arkoub, 2013).

Photovoltaic systems produce direct current (DC). However, most consumers require alternating current (AC). Specifically, the direct current generated by the photovoltaic is converted to alternative through a DC-AC inverter, a power electronics device with a suitable switching frequency and active power supply (P.M.Rodrigo, 2016). In addition, to smooth out the voltage and avoid much higher harmonics of that of the network, it is required the use of suitable frequency filters before connecting the inverter to the network, so that the produced voltage has a form as close as possible to the ideal sinusoidal curve (Letícia T.Scarabelot, 2018).

2.2.3 Photovoltaic Systems and Grid Connections

Photovoltaic systems are used in small and large scale applications, from small electronic devices to energy generation from solar parks. In addition, they offer the possibility of reducing losses in distribution networks and with the constant increase of developments in the solar power sector, their efficiency has rose up to 40% (Fatima Tahri, 2018).

Autonomous electrical installations are probably the most complete applications of photovoltaic technology. They are systems that operate independently for the purpose of supplying specific consumption, without being connected to large centralized electrical distribution networks (V.Salas, 2015). They are the ideal solution for decentralized areas located far from the main grid and their interconnection would require large economical capital. In addition, they are used for desalination, pumping and water purification as well as for street lighting systems, telecommunication systems and agricultural applications (R.Reshma Gopi, 2018). Moreover, there are devices (batteries) that store the generated electricity in order to cover the load during the time that the systems are not exposed to solar radiation, while in the case of alternating current loads there should be an inverter in the system that will convert the constant to alternating voltage (J. Li, 2014).

In grid-connected photovoltaic systems, the photovoltaic electricity produced covers the load and if there is excess electricity generated (surplus), it is transferred and sold to the network. However, in cases where the energy from photovoltaics is not sufficient to cover the demand then the grid provides the complementary energy (S. Ben Mabrouk, 2017). Thus, in interconnected systems there are 2 electricity meters. One calculates the energy exported to the grid and the other the energy that the grid supplies. Also, in the case of interconnected systems, the use of storage is not usually required and consequently the costs of installation and maintenance of the system are reduced (Asma Triki-Lahiani, 2018).

2.2.4 Energy Efficiency and Power Output of PVs

In photovoltaic systems the solar radiation that is absorbed by the surface of the panels is their input power. Moreover, the proportion of the input power to the output is determined as the energy efficiency of PVs or as the 1st law of photovoltaic systems and is given by the following equation:

$n_I = \frac{VmIm}{IsA}$ (Fatih Bayrak, 2017)	(2.3)

The energy output is a result of the current and the voltage of the photovoltaic systems. Even in cases that there is a continuous solar radiation, this conversion phenomenon is not continuous. Nevertheless, there is a point that is defined as the maximum power point where the open circuit voltage of the system (V_{oc}) is higher than its voltage value (V_m). At the same time, the current I_m is low but it has almost the same value as I_{sc} which is the short circuit current (Ahmed Bouraiou, 2017). The maximum power point is determined as the fill factor and it is descripted by the following equation:

$FF = \frac{VmIm}{VocIsc}$ (Fatih Bayrak, 2017)	(2.4)

By combining the previous equations another type of the energy efficiency can be acquired and it is indicated by the following equation:

$n_I = \frac{VocIcsFF}{IsA}$ (Fatih Bayrak, 2017)	(2.5)

2.2.5 Photovoltaic Systems in Greece

In Greece the most widespread use of solar energy is solar water heaters. With regard to the generation of direct electrical energy, the initial photovoltaic systems were introduced in Greece in the 80's by the Public Power Corporation (PPC) mostly in isolated islands. The principle motivating forces for their adoption were the long distance of the islands from the main grid, as well as the fact that they don’t produce any absence of noise (G. Tsilingiridis, 2013). The expensive cost of installation combined with the low efficiency of the photovoltaic panels for this period of time, were the main barriers that resulted to an insignificant market infiltration from the private sector (A.Kyritsis, 2017). This situation altered amid the late 90's when photovoltaics began to get promoted by the country's legislation for many projects. In 1997 a governmental program called "Energy" offered significant subsidies for PV installations (50% to 55% of their investments), until 2001 where it was trailed by the Operational Programme of Competitiveness which offered a 50% subvention for investments of photovoltaic systems (G.Martinopoulos, 2018).

The significant penetration of the photovoltaic technologies in the Greek market rose sharply after 2008 when private house-owners installed rooftop PVs and were funded by the bank or private companies through loans, and the situation for licenses moved toward becoming easier for large and medium scale implementations, resulting to their massive increase that can be illustrated in Figure 10. The reason for this was because they were considered an investment that has a short-term payback period and a high positive net present value (G.Martinopoulos, 2018). The country's legislative framework was beneficial on the adoption of the photovoltaics and this resulted to more than 7500 applications for PV installations (European Commission, 2017).

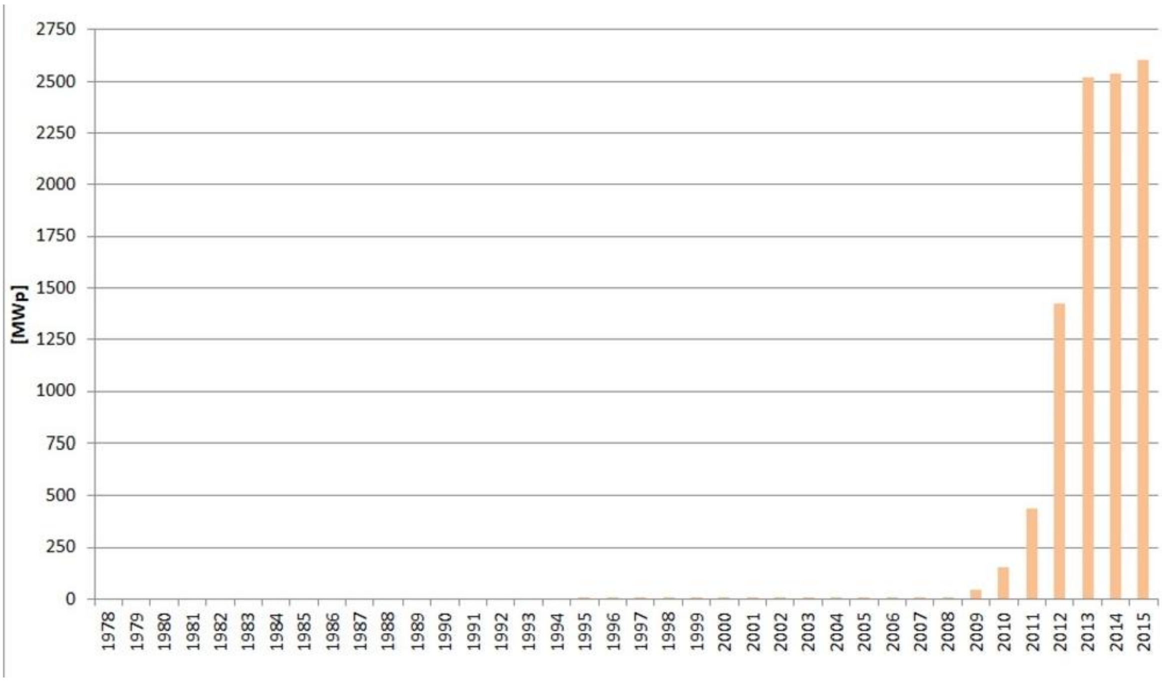

Figure 10: Evolution of the installed capacity of photovoltaics in Greece (G.Martinopoulos, 2018)

Especially the last 5 years the nation implemented notable price decreases for smaller PV installations and higher for larger PV installations, because the target of electricity generation from photovoltaics was achieved earlier (Georgios Tsantopoulos, 2014). This drove the market to a retardation, which was just beaten when the net – metering plan for family units was presented at the end of 2013 (M. Karteris, 2013). Nowadays, Greece has an overall installed capacity of photovoltaic systems at 2605 MWp, including not only all the installations in the mainland that are connected to the grid but also the remote autonomous islands (G.Martinopoulos, 2018). Additionally, for the period of time mentioned above, the generated energy from the utilization of photovoltaics in Greece has been heavily increased. Furthermore, the generation of electricity from photovoltaics in the country until 2011 was under 500,000 MWh and between a 4years period until 2015 it rose sharply, leading to an annual generation of 4,000,000 MWh.

Figure 11: Spatial distribution of photovoltaic installation capacity in Greece for 2015 (G.Martinopoulos, 2018)

The distribution model of PVs in Greece is unique as there are 6 administrative areas with almost the same installed capacity as they are presented in Figure 11 above. It is also notable that besides of Crete, which includes a 3.64% of the whole installed capacity, in other Greek islands their share is nearly negligible and despite the fact that they possess high solar potential, the energy required is actually generated by diesel power generators (G.Tsilingiridis, 2013). Moreover, as it can be seen from the same figure below the percentages of the installed capacity of photovoltaics of Epirus and Western Macedonia are 5.02% and 4.51% respectively. Comparing to the other mainland regions of the country these percentages are lower due to the fact that these areas are mountainous and they do not favor the installation of PVs.

2.3 Wind Energy

In a worldwide scale wind energy has shown a notable increase because of the depletion of fossil fuels, as well as, the emissions they produce. Specifically, by the end of 2016, the entire installed wind capacity of the planet is 486.66 GW (Guorui Ren, 2018). Wind energy is defined as the kinetic energy of the wind due to the heating of the surface of the earth by the solar radiation, which causes the transfer of large air masses from one region to another. It is an inexhaustible primary source of energy while the negative environmental effects resulting from its use are minimal (Tony Burton, 2011).

2.3.1 Wind Turbines Operation

The exploitation of wind in order to produce energy is achieved through wind turbines which convert the kinetic energy of the wind to electrical energy. They are usually organized in wind farms because they are used to a large extent in locations with high wind potential and also visual nuisance from wind turbines is limited to specific areas (Nelson, 2009). Electricity generation from them is significantly unlike from conventional production methods. The operation of the wind turbine is based on two conversion systems electric power:

a) The mechanical system which transforms the kinetic energy of the wind into mechanical torque on the rotor.

b) The electric system, in which the generator converts its mechanical torque rotor in electricity.

In recent years, the wind turbine sector has achieved a remarkable development in terms of design and technological developments with various applications which constantly improve the power output, minimizing the costs and increase the efficiency and stability of the wind turbines (Tony Burton, 2011).

2.3.2 Wind turbines classification

Wind turbines can be categorized according to many different parameters. Regarding the formation of the rotating axis of blade rotors, they can be separated into the horizontal-axis and the vertical axis as illustrated in Figure 12. Nowadays, the most widespread type of wind turbine is the horizontal-axis, in which the wind stream and the rotating axis of the blades are parallel (Juan M.Carrasco, 2011). This kind of turbine has many benefits such as high efficiency, high energy density, low cost per unit of electricity output and small cut-in wind velocities and are suitable for large-scale electricity generation (Vincent F-C.Rolin, 2018).

The axis of the vertical-axis wind turbine is perpendicular to the base of the ground. This type of wind turbine has an important advantage which is that can receive air masses from any direction and so no yaw audit is required (Antonio Posa, 2016). Considering the fact that many of the principle turbine mechanical parts can be installed on the ground, it facilitates the development and built of the wind turbine and as a result it decreases its cost (Rakesh Kumar, 2018). Nevertheless, there is a necessary requirement in order to achieve the rotation of the blades throughout the initialization, which is the exploitation of an external energy source. Due to the fact that the axis of the vertical-axis turbine is holding up on one end at the ground, its upper limit of its height is reduced although they require less maintenance (Antonio Posa, 2018). Vertical-axis turbines have a more limited utilization comparing to the horizontal-axis because they generate less energy, have lower efficiency and lifetime and they are considered less reliable (Iris Hui, 2018).

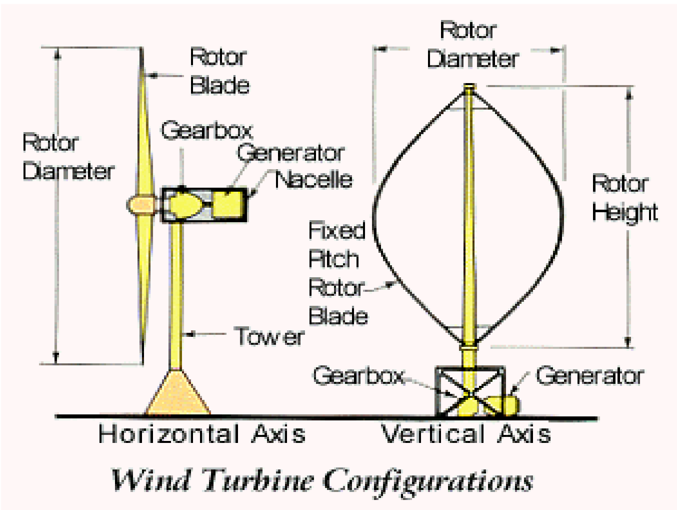

Figure 12: Horizontal axis and vertical-axis wind turbine (Renewable Energy Sources , 2009)

According to the formation of the rotor, the horizontal-axis wind turbines can be categorized to upwind and downwind turbines. The highest proportion of the installed wind turbines today is upwind type, in which the rotor looks toward the wind. A significant advantage of this type of wind turbine is to prevent the deformation of the flow field as the wind penetrates the wind tower and nacelle (Xin Cai, 2016). Regarding the downwind turbines, initially the wind penetrates the wind tower and the nacelle and then the blades. This system gives more flexibility to the rotors but their power output is not stable and has high fluctuations (Zhenyu Wang, 2018). Moreover, the noise of the blades is higher and due to the lack of stability in the flow field, losses might occur (C.Kress, 2016).

Category	Power Output	Applications
Micro wind turbine	P< Several kW	In remote off-grid locations and can be used for water pumping and street lighting. They require low cut-in speeds and function in medium wind speeds.
Small wind turbine	P< 100kW	In residential houses, farms and generally in isolated instalments like water pumping stations. They increase the electricity production and limit the requirement of higher transmission lines capacity.
Medium wind turbine	100kW<P<1MW	Suitable for hybrid energy systems villages and small islands for both connected and not-connected systems.
Large wind turbine (Megawatt)	P<10MW	Used in the majority of wind farms, especially the offshore.
Ultra-large wind turbines	P>10MW	Initial stage of evolution.

Table 1: Wind turbines categories according to their capacity (Tong, 2010)

Table 1 above summarizes the categories and the applications of wind turbines according to their power output range. Additionally, wind turbines can be applied for systems connected to the grid or autonomous. The majority of medium and large turbines are used in those interconnected systems and because of that they don't require storage devices (batteries) (Yu Luo, 2017). On the other hand, wind power is an intermittent source of energy that depends on the location and the climatic conditions. Thus, for off-grid systems especially in remote and isolated areas such as islands, the wind turbines must be connected to batteries, diesel engines and other energy and storage systems in order to achieve a better and more stable wind power generation (A.Lorestani, 2018).

2.3.3 Wind power output and capacity coefficient

The power output of a wind turbine varies with the wind velocity, and it depends on it its geometrical characteristics and its design.

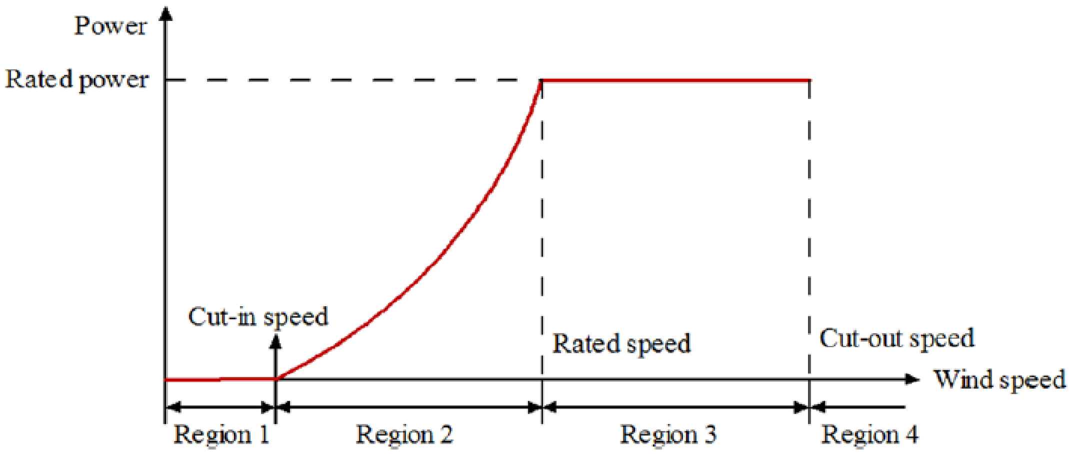

Figure 13: Typical power curve of a wind turbine (Rahul Dutta, 2014)

The power curve of a wind turbine can be defined as the graph of its power output for each wind speed value (Figure 13). It is characterized by the start-up speed ($V_{cut\text{-}in}$), which is the slowest speed from which the wind turbine starts to produce power. This power output is constantly increasing alongside the increase of the wind velocity until reaching a maximum limit, where the power output has obtained its highest value determined as the rated power. Subsequently, the speed at this limit is determined as the rated speed (V_{rated}). After this limit, if the wind velocity continues to increase the operation of the turbine must be stopped in order to avoid damages and it is defined as the cut-off or cut-out speed ($V_{cut\text{-}out}$). So, it is obvious the wind turbine produces its rated power, when the wind speed varies between the cut-in and the cut-off limit (Tony Burton, 2011).

The conversion of wind power to electricity can be defined by the equation below:

$P_{eff}= \frac{1}{2}(C_p \rho A V^3 n_{gear} n_{gen} n_{ele})$ (Tong, 2010)	(2.6)

Where P_{eff} (W) is defined as the effective power output of the turbine, ρ (kg/m^3) the density of air, V (m/s^2) the wind velocity and A (m^2) the area of the blades considering their length (R) as the radius of this circle area. Moreover the efficiencies of the gearbox, the generator and the electric are defined as n_{gear}, n_{gen} and n_{ele} respectively. Regarding the power coefficient (C_p) of the wind turbine it is determined as the ratio of the power obtained by the blades of the turbine to the available power of the wind.

$C_p = \frac{\text{Pavailable}}{1/2 \rho A V^3}$ (Tong, 2010)	(2.7)

The value of the power coefficient is varies from 30% to 45%. This is due to the fact that in the wind turbine installations aerodynamic losses can occur and thus resulting to a lower value of the power coefficient.

2.3.4 Wind Energy in Greece

In Greece, efforts to exploit wind power for electricity generation started in the early 1980s by PPC and the middle of the 1990s the exploitation of wind power has been greatly stimulated by facilitating investments by individuals (A.M.Papadopoulos, 2008).

Figure 14: Distribution of wind power in Greece (Nikos E. Mastorakis, 2010)

Over the last decades, the application of wind farms has gained attention mainly from various construction companies and investors from the private sector. The exploitation of wind energy is considered a challenging field of development in Greece especially in regions with poor infrastructure, in which high wind potential can be found (Nikos E. Mastorakis, 2010). Many wind farms have been installed in various areas of the country and their distribution is depicted in Figure 14 above.

During a 10 years period, between 2005 and 2015 the installed capacity of wind power in Greece has shown a notable increase as it can be seen in Figure 15 below by exceeding 1.5 GW (Dimitrios Angelopoulos, 2017). Consequently, the 2020 national target which aims to a 7500MW installed wind capacity appears to be very optimistic because of various legislative issues and the weakness of the isolated grids (especially in Aegean islands) to support large units (Mary Christoforaki, 2017). Over a 10 year period between 2005 and 2015 the installed wind power of Greece has shown a notable increase.

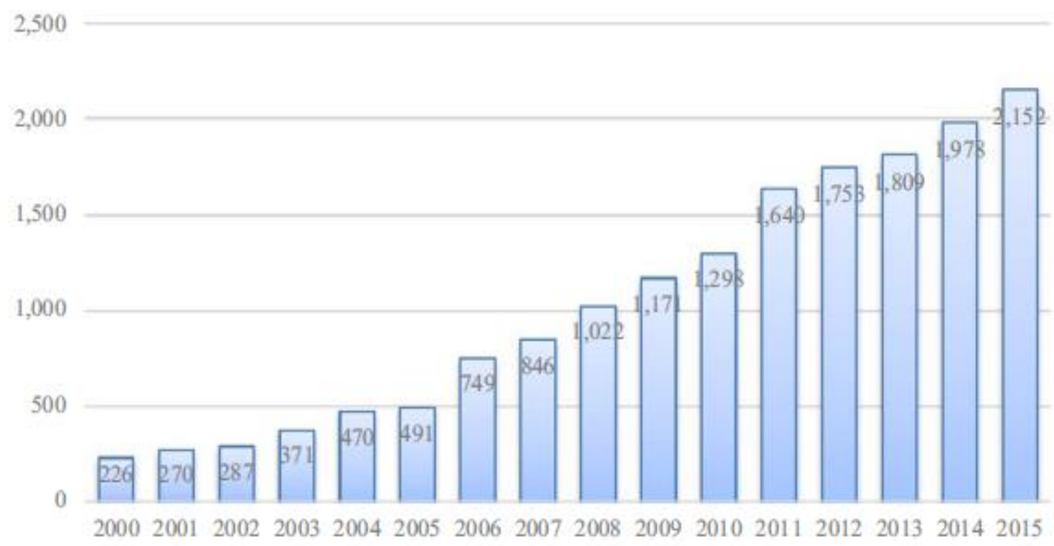

Figure 15: Total installed wind capacity (MW) of Greece per year (Dimitrios Angelopoulos, 2017)

So despite the notable growth of installed wind power in recent years, it is obvious that this increase is too small given the fact that Greece has high wind potential. Furthermore, one other reason that creates difficulties in the full exploitation of this potential is due to the lack of interconnection in the Aegean island system (Xydis, 2013). Additionally, the intense variations and fluctuations, which are the main features of wind energy due to its intermittency, reduce the possibility of their installation (Emmanouil Voumvoulakis, 2012).

The average annual wind speed in many parts of Greece, is at extremely high levels for production of electricity and with a proper exploitation, it can contribute significantly in the improvement of Greece energy balance (Margarita Vasileiou, 2017). Furthermore, those wind speeds can overlap the efficient wind speed range for wind turbines and can cover the electricity requirements of these islands (M.Kapsali, 2017).The most favored in terms of wind potential areas of the country are located in the Aegean, mainly in the Cyclades, Crete, in Eastern and Southeastern Peloponnese, Evia and East Thrace. According to studies and estimations based on information about the average wind speed there is the possibility of installation and operation of offshore wind farms with a total power potential of almost 1000TW (European Environment Agency, 2009).

On the other hand, due to the lack of interconnection with the national grid there is no possibility of exporting electricity surplus during periods of low demand and solutions such as implementations of suitable hybrid energy systems with storage units are required (Georgios N. Psarros, 2018). Moreover, because of the small size of the majority of the Aegean islands, residents are reacting to the installation of wind farms with their main concern to be that wind turbines will have a negative effect on tourism by spoiling the landscape of the islands (Alexandros Dimitropoulos, 2009).

2.4 Storage

Nowadays, the constant utilization of fossil fuels has resulted to the pollution of the environment due to the CO_2 emissions. Thus, the exploitation of renewable energy sources has become necessary in order to acquire a more secure and sustainable future in a worldwide scale. One characteristic of renewable energy sources is their intermittent nature (Solar and Wind). As a result, their integration to large-scale electricity networks or autonomous Hybrid Energy Systems in remote and isolated areas is complicated because of their inability to produce continuous energy to meet the current demand especially in peak-time hours (Brunet, 2011). This situation has created the requirement for implementation of energy storage devices, which can store the energy produced during periods of high supply and supplying it during periods of high demand. Moreover, the purpose of installation storage power units is not only to use them in times when the energy production from RES will not cover the load, but also to normalize the power output of RES systems (Y.K. Zeng, 2016).

2.4.1 Electrical Storage Devices Technology

Most applications of energy storage revolve around the storage of electrical energy due to its simple transportation over long distances. The storage of electricity is achieved through its conversion into another form of energy. There are various systems that store electricity with different parameters and elements, as well as, costs of installation and maintenance.

Electrical energy storage systems	**Characteristics**
Pumped storage hydropower	Systems that store energy related with a raised amount of water by pumping it from the low-height to the upper-height reservoir. They possess the highest percentage of installed energy storage capacity in a global scale.
Compressed-air energy storage (CAES)	In these systems devices exploit the excess electricity and compress and store the air. In the next stage through a gas turbine this air is realised in order to produce the required electricity.
Batteries	These devices convert electrical energy into chemical and their implementation is taking place for more than a century. There are various types of batteries relying on different chemical reactions.
Thermal energy storage	These systems store heat and use it in order to generate electricity. Their application is mainly found in solar thermal power units.
Flywheels	These mechanical systems through the aim of motor generators store energy in the form rotating mechanical energy and release it in the form of electricity very quickly.
Capacitors (Super-capacitors)	They have the potential of storing electrostatic charge directly. Thus they respond immediately to load variations, although they produce limited amount of energy.
Super conducting magnetic rings	Similarly with capacitors, they store electricity directly by utilizing the properties of the magnetic field related with the circulating current.
Liquid energy storage	These systems store energy by converting and storing electricity into liquefied air. They are still in experimental stages.
Hydrogen storage	These systems use hydrogen which is released by the electrolysis of water and can be produced by using the surplus electricity.

Table 2: Electrical Energy Storage Systems (Frank S. Barnes, 2011)

Moreover, factors such as their response time on delivering power and their efficiency can distinguish them and determine their implementations (Jingzheng Ren, 2018). These storage systems and their characteristics are described in Table 2 above.

An important factor that affects the selection of these systems is the efficiency of the energy transformation procedure. This process consists by 2 stages the electricity storing and its retrieve, with losses including in every stage. The ratio of the stored electricity to the retrieved is defined as the round trip efficiency (Breeze, 2018). The round trip efficiency is not the same for all the energy storage systems as it is presented in Figure 16 below. From this figure it is worth mentioning that the storage technology based on mechanical systems such as flywheels, pumped storage and compressed air (CAES), have lower round trip efficiency in comparison with the other energy storage technologies and are less efficient, although they have the potential to of storing energy for long periods of time. Capacitors and batteries can perform well although their efficiencies are reducing with time, while flow batteries can be very efficient and have a better maintenance of their round trip storage efficiency over time (Breeze, 2018).

Energy Storage Technology	Round Trip Storage Efficiency (%)
Capacitors	90
Superconducting magnetic energy storage	90
Flow batteries	90
CAES	65
Flywheels	80
Pumped storage hydropower	75–80
Batteries	75–90

Figure 16: Round trip energy storage efficiency for different storage systems (Breeze, 2018)

2.4.2 Batteries

Batteries have the ability to store electricity by converting it to chemical energy and release it the appropriate time to cover the load. They possess an electrolyte which is located between the battery electrodes. They are used to store large amounts of energy and they are designed in order to be charged and discharged up to a few thousand times, depending on their type and application. However, large discharges during their utilization reduce their life span (Zito, 2010). They play a key role for the integration of renewables into the grid by improving its stability and for this reason new technologies and developments are constantly making their appearance. Furthermore, due to their simple maintenance requirements, high electricity conversion efficiency and adoptability to various applications, they considered as a necessary installation especially for micro-grids and stand-alone systems of distributed energy resources in isolated areas where electricity supply is a challenging procedure due to the intermittency of the renewable energy sources and their inability to cover the demand at any time (Pan H., 2013).There are many different types of batteries with different parameters and characteristics such as lifetime, energy conversion efficiency and cost.

2.4.2.1 Lead-Acid Battery

Over the last century, lead-acid batteries are the most dominant type of battery in use and their production is constantly increasing. The reason that this battery has the most successful penetration in the market, comparing with the others, is because it has low cost, high reliability and operational security, easy implementation and a relatively developed recycling technology (Pavlov, 2017). Their installation is mainly applied in the sector of transportation (vehicles), telecommunication and small-scale power systems. Additionally, lead-acid batteries are considered to be the most cost-effective choice and have inexhaustible resources for their construction due to the fact that 95% of their material can be recycled (Tayyeb Nazghelichi, 2018).

However lead-acid batteries have certain disadvantages. First of all, the fact that the majority of them have a small life cycle makes them unsuitable for large-scale energy applications. They also have low energy density, low efficiency and reduced depth of discharge. Furthermore, they cause pollution of the environment because of the toxicity of the lead (Qin Yang, 2018). Finally, their operation relies on temperature and as a result during the charging procedure problems with temperature increase occurs, while their performance drops during lower temperature conditions (F. Torabi, 2013). Nevertheless, the new and advanced versions of lead-acid batteries have led to improvements in the frequency of maintenance, environmental pollution and self-discharge time.

2.4.2.2 Lithium-ion Battery

Lithium-ion batteries are one of the most wide-spread types of battery and their applications can be mainly found in portable electronic devices and in electric vehicles. In 1990 they made a significant market penetration by SONY. They have also high potential of supporting the integration of RES in the electricity grid or in stand-alone power supply systems (Feng Zheng, 2018). The reason for this is because this battery has high energy density, operational voltage and round trip efficiency. Moreover, it possesses a long life-cycle, low discharge rate and low maintenance cost and it is considered environmental friendly due to the various eco-friendly materials used for their chemistry (Ghassan Zubi, 2018).

On the other hand, there are some specific drawbacks. During the operation of those batteries many thermal accidents such as fire or explosion have been reported, due to the fact that there is a lack of thermal stability and a low fire point (Binbin Mao, 2018). Furthermore, they have an expensive initial cost, a poor recycling technology and in order to operate properly, battery management systems need to be implemented (Junfu Li, 2018). However, many researchers have shown great interest on improving the thermal stability by developing various fire control strategies.

2.4.2.3 NiCd Battery

Another electrochemical system is the Nickel-Cadmium (NiCd) batteries. These storage devices have high energy density and durability, remarkable life-cycle and a relatively low-purchase cost. They are suitable for DC power supply due to the fact that they can be recharged quickly and have a normal discharge rate (Ghassan Zubi, 2018). One other characteristic of these batteries is their small resistance and their low operational and maintenance cost. At Golden Valley, Fairbanks, there is one of the strongest batteries in the world, which can offer 40MW for 7 minutes and is used to stabilize the island network (Patrick T.Moseley, 2015).

In the modern market, NiCd batteries sales have been decreasing for over a decade because of the effects of toxic cadmium and because battery technology is no longer justifying their cost for some applications (Kun Ding, 2016). Regarding their use in some RES systems, they prove to be an inappropriate and unsuitable due to their particular memory effect. If they are not fully discharged before a new charging cycle starts, the batteries begin to lose their power (Ghassan Zubi, 2018). Lastly, due to their dependency on cadmium which is a hazardous element, their adoption and utilization has been constrained by various legislations.

2.4.2.4 NiMH Battery

Nickel-Metal Hydride (NiMH) batteries are an extension of the technology applied to nickel cadmium batteries, with the main difference being that instead of cadmium they use a metal M hydride (Valentina Innocenzi, 2017). The use of this metal eliminates the environmental impact of NiCd batteries, while reducing the memory effect. The specific energy and round-trip efficiency of this battery are in satisfactory levels, while they operate under acceptable temperature limits and thus providing high reliability (Eduardo H.Tanabe, 2016). More advantages of this storage device are their low operational and maintenance cost, their good history of safety and their ability to recharge in a relatively fast rate. An additional reason that these systems start to replace the Nickel-cadmium batteries is their higher capacity which ranges among 40% to 50% (Hoffart, 2015).

However, their initial cost comparing to the NiCd batteries is higher, as well as their rate of self-discharge (Wenhua H.Zhu, 2014). Another disadvantage of those batteries is that their life-cycle is considered relatively low and their recycling schemes are poor. NiMH technology has reached a high degree of maturity for a variety of commercial applications, including low power applications such as portable electronic devices, to high power applications such as hybrid electric vehicles (Wenhua H.Zhu, 2013).

2.4.2.5 Redox Flow Batteries and Vanadium Redox Flow Batteries

Redox Flow Batteries (RFB) are considered to be one of the more advanced category of electrochemical energy storage and their development has shown a notable increase over the last 30 years. One of the battery's electrolytes is stored in a liquid form outside and during the absorption or production of energy it flows to the cell where the electrochemical reaction occurs (Kleber Marques Lisboa, 2018). What is achieved with the flow batteries is the decoupling of the energy density, which is mostly associated with the size of the storage tank and power density, which is mainly determined by the size of the battery. Self-discharge is also negligible, and the depth of charge-discharge cycles does not affect battery viability (Mike L. Perry, 2016). All of these features make flow batteries more flexible for a wider range of applications than common ones. They are ideal for large scale energy storage applications due to the fact that they are flexible of controlling the power independently capacity and thanks to their adaptable scale-up alongside with their cost-effectiveness, they can be combined effectively with RES systems. In addition, these batteries have a very fast response and they are able to shift from charging to discharging in 1ms due to the small duration of their chemical reactions (Rajagopalan Badrinarayanan, 2017).

Vanadium Redox Flow Batteries (VRB) in the last 20 years have been tested and installed in various areas and have been classified as the most environmentally conscious storage system. This type of battery stores energy using vanadium redox couples and it can be used in isolated systems to stabilize RES operation by absorbing fluctuations, for power optimization. With an appropriate annual maintenance, these batteries have a low self-discharge time, reach a long lifetime and even fully discharged without electrolyte wear (Zhongbao Wei, 2018). In addition, they can be upgraded at a relatively low cost by replacing the storage of electrolytes with other larger volumes, or by adding additional electrochemical cells to increase power. As far it concerns safety issues, the cross mixing of electrolytes reduces the likelihood of contamination (M. Skyllas-Kazacos, 2011). Moreover, its materials are not inflammable and have significantly lower levels of toxicity than other components of batteries. One challenge that needs to be addressed is the poor energy density of these batteries (less than 0.1 W/cm^2) and their relatively high initial cost (Matthäa Verena Holland-Cunz, 2018). Due to this challenge, they require a large space for their installation. VRB are suitable for a range of energy storage applications for electricity and industrial consumers, although the majority of technology development projects focus more on stable applications due to their low energy density. These include improved power quality with voltage smoothing, peak shaving, increased power supply security and integration with RES systems (Frank S. Barnes, 2011).

2.4.3 Importance of storage in Islands

Renewable energy production is intermittent and therefore unable to follow the load demand curve of a network. It shows intense fluctuations as it is based on unpredictable meteorological data. Consequently, this energy may not be available when required or produces a surplus which is discarded. In small-scale power systems electrochemical storage combined with appropriate wind and solar mixing energy production can be a reliable and economical solution. These storage systems may be developed as decentralized (micro-grids) or as one (or more) central storage systems combined with wind farms and photovoltaics (Zdeněk Dostál, 2018).

In off-grid electrical systems such as those of many Greek islands where the wind and solar potential are high, a substantial part of them remains unexploited due to the lack of suitable storage (E.D. Giannoulis, 2011). The production of photovoltaics during the day has its peak at midday hours and it becomes necessary to store the surplus energy produced at that period of time in order to be used and cover the night load. This results in the need to store time-shifted production energy from RES in the form of another energy and be transformed into electricity when this is required in times of loss of RES (for instance in zero periods sunshine or very low wind speed) (Notton, 2015). Furthermore, wind energy is considered an economically available energy source for electricity storage systems on the islands, because the demand for electricity energy is fluctuating widely over the 24-hour and seasonal periods (especially the summer due to the high rates of tourism). Subsequently, the large penetration of wind power encounters problems at low demand times (during night hours) when wind power generation occurs, resulting in rejection of this extra energy (M.Kapsali, 2017). Therefore, this excess electricity from the wind (surplus) can be exploited by the implementation of appropriate storage systems.

The benefits of storage in the islands, apart from the large wind and solar energy penetration, are many. There is the potential of reinforcing the grid, discharging transmission networks and improve its reliability, quality and stability (N. Mahmud, 2016). It can also bring savings in operating costs or capital investments, ensures economic function of the system as a whole with limited or even zero CO_2 emissions and increases the energy security of these regions by decreasing the dependence on the imports of fuels (Yuqing Yang, 2018). Thus, the technology of electrochemical storage systems (batteries) which are constantly upgraded, alongside the integration of renewable energy sources in the grid, are suitable for applications in remote islands that mainly use diesel power generators in order to cover their energy requirements (Sandrine Selosse, 2018).

2.5 Conclusions

According to the information revealed in the sections of the literature review the following conclusions can be drawn:

- The exploitation of renewable energy sources in Greece is still in early stages, despite the fact that the country has high potential, with some significant steps made over the last decades.
- The climate and the location of the off-grid Greek islands of the Aegean Sea, which rely on diesel generators to cover their energy needs, favour the exploitation of wind and solar power (high wind speeds and solar radiation).

- Hybrid Energy Systems which combine solar and wind energy with diesel generators are a suitable solution for those islands. They can contribute significantly on improving their energy security and reduce their carbon emissions and their dependency on fuel imports.
- Because of the intermittent nature of wind and solar energy, storage is necessary for a stand-alone energy system for these islands.
- For small scale off-grid power systems electrochemical devices (batteries) are one of the most wide-used storage systems. The most suitable types of batteries for integration with renewable energy sources are: Lead Acid, Lithium-Ion and Vanadium-Flow.
- Consequently, the components of the hybrid energy system that will be modelled for a not-connected Greek island will be: photovoltaics, wind turbines, diesel generators and different types of batteries. Their economic details will be mentioned in the next sections.

3 MATERIALS AND METHODS

This chapter begins by presenting the software tool selected in order to achieve the aim of this project. Then, it follows a description of the case study and the inputs for the simulations and finally the different scenarios of the simulations for the various combinations of hybrid systems are analysed.

3.1 Software Tool

3.1.1 Introduction

During the process of designing a stand-alone electricity generation system, a number of decisions must be taken to establish that it is properly set up and functioning, such as what kind of elements and inputs should be included in the system. The variety of the available technologies in the market combined with the renewable energy potential of the current examined area, as well as the cost of each system and component, make these decisions more complicated.

	MERIT	**HOMER**	**ENERGY PLAN**
Cost	Free	21 days free trial £10 for Students	Free
Adaptability	Medium	High	Medium
Scale suitability	Community scale	Community scale	National/regional
User friendly	Medium	High	High
General	Suitable for modelling demand, generation and storage and presents results regarding the match of the demand and supply. It contains technical analysis of the results while parameters such as the cost, are calculated outside of the tool.	It has similar potentials with Merit, but with higher techno-economic assessment for the hybrid energy systems. It presents the results according to the lowest net present cost and it is able of carrying out sensitivity analysis.	Suitable for modelling energy systems in a national and regional scale with high techno-economic analysis. Nevertheless, on a community scale this tool is not so adaptable.

Table 3: Characteristics of relevant software tools for energy modelling (Andrew Lyden, 2018)

There are various software tools available for sizing and optimizing power generation systems. In Table 3 above, the most associated with the case study of this project are illustrated.

HOMER software, which was chosen for the case study of this thesis, contributes to the simplification of those factors that affect these decisions and it is considered one of the most wide-used software tools for the design and optimization of off-grid hybrid energy systems (Muyiwa S. Adaramola, 2014). It was developed by the National Renewable Energy Laboratory, initially as a community-scale model that simulates different RES systems installations for stand-alone electricity generation systems and then augmented for grid-connected and thermal systems as well (Andrew Lyden, 2018).

HOMER contains and performs 3 main functions: simulation, optimization and sensitivity analysis. In the first process, the performance of a particular hybrid system is analyzed and then the load cover and the net present cost are calculated. In the optimization process, many different configurations of hybrid systems are analyzed and the one that satisfies the technical restrictions and at the same time has the lowest net present cost is identified. In the last process, many optimizations are carried out with a series of assumptions expressed by introducing the sensitivity analysis variables (fuel cost, wind speed, etc.) (Hassan Zahboune, 2016). Specifically, HOMER software is a tool for optimizing the design of hybrid power generation systems. When designing a hybrid energy system, many elements need to be taken into consideration such as:

- The components that should be included in the HES (wind turbines, diesel generator, PVs, batteries, etc.)
- The number of those components and their size (for instance, 3 WT of 100kW each)
- The HES with the lowest cost

The large number technology choices, the variations in economic and technological costs and the availability of energy resources make the selection for the decisions of the hybrid energy system difficult. HOMER's sensitivity analysis optimization functions make it an easy-to-use tool in evaluating alternative energy system configurations (Anand Singh, 2015).

3.1.2 Data Input and Output

In order to use HOMER, it is necessary to include the input data which describe the components options. These include, among other things, elements such as expected wind speeds, solar radiation, load demand data, operating and maintenance costs of the system, initial cost of investment, etc. The program uses these input data to simulate the different designs of hybrid systems or combinations of system components and produces the results shown in the list of achievable designs and which are cost-based (Getachew Bekele, 2012).

HOMER presents the results of the simulation in the form of tables and graphs that help compare systems and assess them according to financial and technical characteristics. In order to undertake a sensitivity analysis, the sensitivity values that describe a range of costs, as well as, the elements of the renewable energy sources of the system are required. It analyzes each design of the hybrid systems and the results of this process can be used to determine the factors that have the greatest effect on both the design and operation of an energy system (Muyiwa S. Adaramola, 2014). Figure 17 below indicates a schematic representation of this tool with the input and output data.

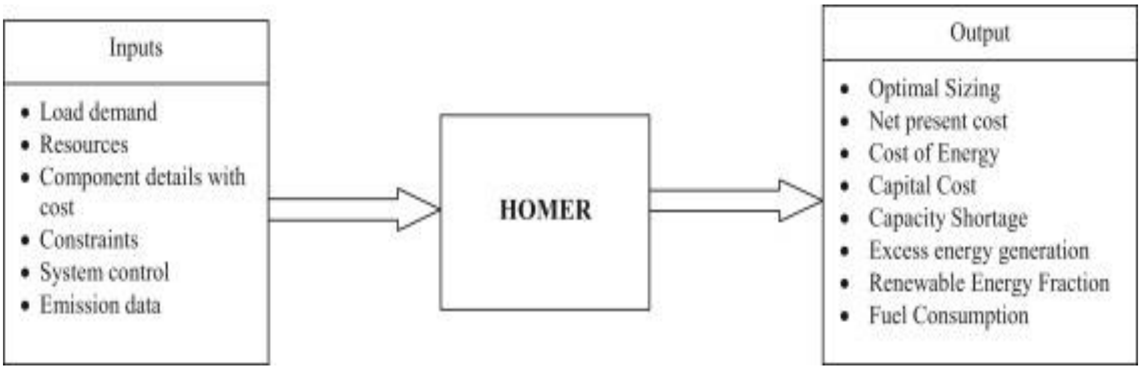

Figure 17: Representation of inputs and outputs of HOMER (Sunanda Sinha, 2014)

3.1.3 Simulation

Homer's main potential is to simulate the long-term operation of an electricity system. Sensitivity analysis and optimization capabilities are more specialized and based on the simulation capability. During this process it is determined how a specific configuration with components of a particular size and an operating plan that determines how these elements work together, will work over time and in a given environment (Getachew Bekele, 2012).

Firstly, it examines the technical feasibility of the system by simulates the operation of an energy system using all the energy calculations made for each simulation time step (usually 1 hour time-step) over a year (Prinsloo G., 2016). In other words, HOMER runs the whole year with the time-step that has been set by calculating the availability of renewable energy sources and comparing it with the demand and deciding how to manage the surplus of electricity produced or how to produce (or import from the grid) energy to cover the load in periods of deficit. When these calculations are completed for the whole year, it determines if the system meets the user-defined limitations (Hassan Zahboune, 2016). These restrictions may relate to the percentage of cargo served, the rate of penetration of renewable energy sources, pollutant emissions, etc. For systems that contain batteries or fuel generators (diesel generators, biomass generators, etc.), HOMER also determines on each step how the generators will perform or how the batteries will be charged and discharged (H.Rezzouk, 2015).

Finally, it decides whether a combination is feasible and specifically if it can meet the demand for electricity and if it can calculate the cost of this hybrid system. Cost calculations of systems refer to capital cost, replacement and operating costs and maintenance costs. The program simulates the operation of the system for one year and considers them to be representative of all other years of the estimated total life of the system (Rohit Sen, 2014). It does not take into account changes such as increasing demand load or reducing battery performance. However, the investigator can examine the effects of such factors by sensitivity analysis.

3.1.4 Optimization

The optimization procedure presents the best possible configuration of the system, opposite to the simulation process, which models a particular configuration. For HOMER, an optimal configuration is the one that satisfies all user-defined limitations and has the lowest cost (Kein Huat Chua, 2015). In order to find the optimal configuration of the system, decisions should be made to combine the elements to be included, the size or the quantity of such elements. HOMER simulates many different system configurations, rejects those that do not meet the user's limitations and classifies the other feasible configurations based on their net present cost (Igib Prasetyaningsari, 2013).

3.1.5 Sensitivity Analysis

During the sensitivity analysis process HOMER performs multiple optimizations, for every sensitivity variable input. The objective of the sensitivity analysis is to assess how much the outcomes from the original cases are affected (Kein Huat Chua, 2015). A sensitivity variable can be defined as an input variable which can take many different values and the program does not limit the amount of sensitivity variables that can be set and thus allowing the user to set as many as he wants. Sensitivity analysis is implemented in order to eliminate the uncertainty factor and allow the user to investigate at all the different scenarios that interest him (Rohit Sen, 2014). Additionally, this procedure helps the user to understand the impacts that some factors may have on the system he is planning and to get the most appropriate decisions according to his criteria.

3.1.6 HOMER limitations

In order to operate properly and acquire reliable results, it is essential to be aware of the constraints and limitations of the selected software tool before the simulation of the hybrid energy systems. Some notable limitations of Homer are:

- Numerous objectives issues cannot be formulated because Homer utilizes only one objective for the minimization of the net present cost.
- It does not take into consideration the intra-hour alterability.
- The equations that the program uses are 1^{st} degree linear (Sunanda Sinha, 2014).

3.1.7 Economic Modelling of HOMER

The economic model of HOMER consists of some specific parameters, which are used in order to develop it and assess the results of the simulations. One main parameter is the total net present cost of the system (NPC) and it expresses the difference between the current value of the project over its lifetime and the current value of all its income over its lifetime. The equation that calculates the total net present cost of a project is presented below:

$\mathrm{NPC}=\frac{C_{an,tot}}{\mathrm{CRF(i,R)}}$ (W. Margaret Amutha, 2016)	(3.1)

Regarding the components of this equation the $C_{an,tot}$ (€/year) is the total annual cost (sum of all the annual costs of each component of the system), the CRF expresses the capital recovery factor, i the interest rate in % and R the lifetime of the system (years).

The capital recovery factor is given by equation (**3.2** below:

$\mathrm{CRF}=\frac{\mathrm{i}(1+i)^{R}}{(1+i)^{R}-1}$ (Alireza Haghighat Mamaghani, 2016)	(3.2)

R and i are the number of years of the project and the annual real interest rate, respectively.

Another important financial parameter of HOMER is the cost of energy (COE), which expresses the average cost per kWh (€/kWh) of the useful electricity generated by the system. The following equation presents the calculation of COE for an off-grid power system:

$COE=\frac{C_{an,tot}}{E_{served}}$ (Caroline Bastholm, 2018)	(3.3)

E_{served} is the total amount of electricity that serves the load during the year (kWh/year).

3.2 Case study and input data

As a case study of the project, the Greek island of Donousa has been chosen (Figure 18), which is a small island located in the south-eastern Cyclades, 10 miles north of Amorgos and east of Naxos (latitude 37.7 ^{o}N and longitude 25.48 ^{o}E) . Its area is 13.4 km^2, with many hills and rocks (max 3 miles in diameter) with a maximum altitude of 385 m and a total coastline length of 31 km, with 167 permanent residents in its 4 villages (SOUTH AEGEAN REGION, 2014).

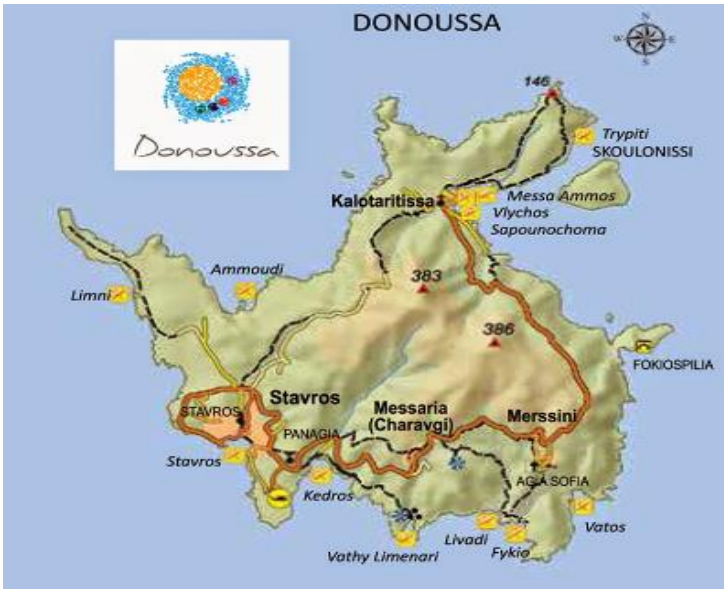

Figure 18: Donousa Island (Cuclades, 2014)

The energy needs of the area are more than double in the summer months due to the fact that Donousa is a popular tourist destination and as an off-grid island its energy requirements are covered by diesel power generators. Its climate is Mediterranean and is characterized by its low thermometric range, mild winter and prolonged dry and cool summer with extensive periods of sunshine. The annual rainfall is also limited and one of the lowest in Greece. The Cyclades, in general, are characterized by the largest number of sunny days during the year in the country. Another important feature of the area is that it has high wind potential, with annual strong winds of mostly northern direction. In general, the island has many advantages in the RES sector development due to its climatic conditions but until today its potentials have remained unexploited (SOUTH AEGEAN REGION, 2014).

3.2.1 Solar and wind potential of Donousa

Donousa is considered a particularly favored island in terms of potential of RES. Homer Pro has the potential of locating from its map the selected study area (either manually or by inserting specific coordinates). Below the details of its wind and solar potential are illustrated. Initially, the data on solar radiation on the island and specifically the clearness index and the daily radiation are shown in Figure 19. In order to calculate monthly averages of sunlight and day-to-day radiation, the measurements of hourly solar radiation over a one-year period were automatically entered into the HOMER PRO program, which has access to NASA weather data.

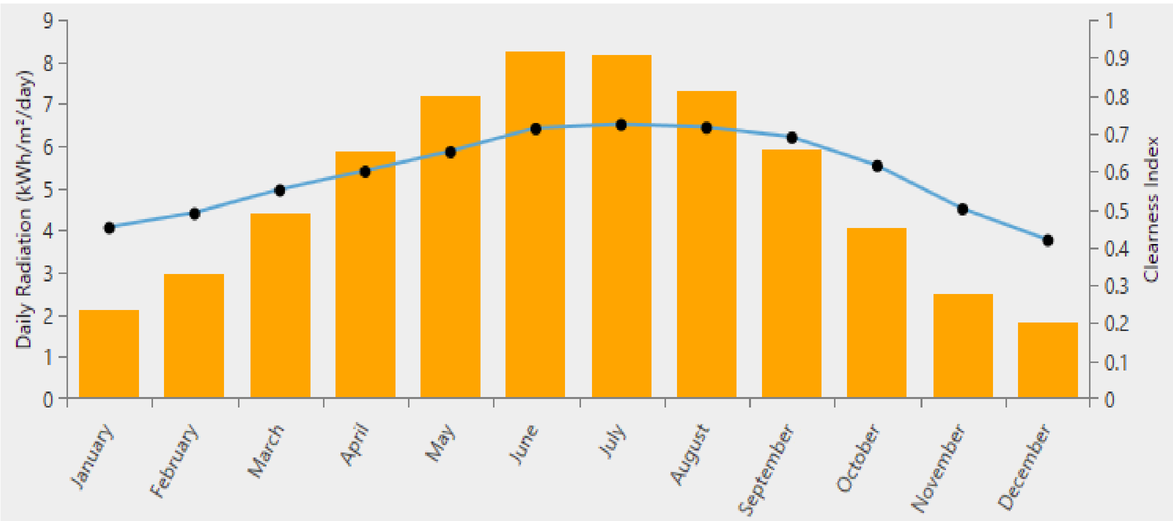

Figure 19: Donousa Daily Radiation and Clearness Index by HOMER

As it can be seen from the graph above, Donousa because of its geographical position has great proportions of sunshine throughout the year. Another advantage of the solar potential of the island is that it has the highest daily radiation and clearness index at the time with the highest demand (during the summer season) with daily radiation exceeding 8 kWh / m^2/day on summer months. The lower values of the daily radiation and the clearness index can be found in December and November. The annual average daily radiation calculated by HOMER Pro for Donousa is 5.05kWh/m^2/day. Another benefit of the island that favors the exploitation of its high solar radiation, is the fact that Donousa has a large amount of acid area where photovoltaics can be installed and operate. Moreover, the island doesn’t have any protection area and for this reason the installation of PVs can be applied without any legislative barriers (SOUTH AEGEAN REGION, 2014).

Regarding the wind potential of Donousa, Homer Pro which has access to the climate and weather data of NASA gave us results about the average wind speed of every month for the island by inserting the longitude and latitude of the region. The velocities of the wind in Donousa for a one year period are presented in Figure 20 below. From this figure it is observed that the highest values of the wind speed can be found during the winter months from December to January reaching almost 8m/s, while during spring and autumn months the rates are relatively reduced. The annual average wind speed calculated by Homer Pro is 6.23m/s.

Figure 20: Average Wind Speed in Donousa by HOMER

Another notable element of Donousa is the fact that large areas in the centre of the island, which have high wind potential because of the altitude, remain uninhabited and their utility is reduced. This fact, alongside the legislation of the Greece which doesn’t contain Donousa in protected areas, facilitates the licensing processes of the installation of wind turbines. Furthermore, the topography of the island which is limited to 4 small villages reduces the potential losses from natural obstacles (SOUTH AEGEAN REGION, 2014).

3.2.2 Load Profile of the island

Regarding the load profile Donousa the data were obtained from a previous project related to this island (Stamatopoulos, 2014) and were imported into HOMER Pro in order to build its energy demand profile. The annual maximum demand value is 180kW (peak load) during August, which is the month with the highest rates of tourism in Greece.

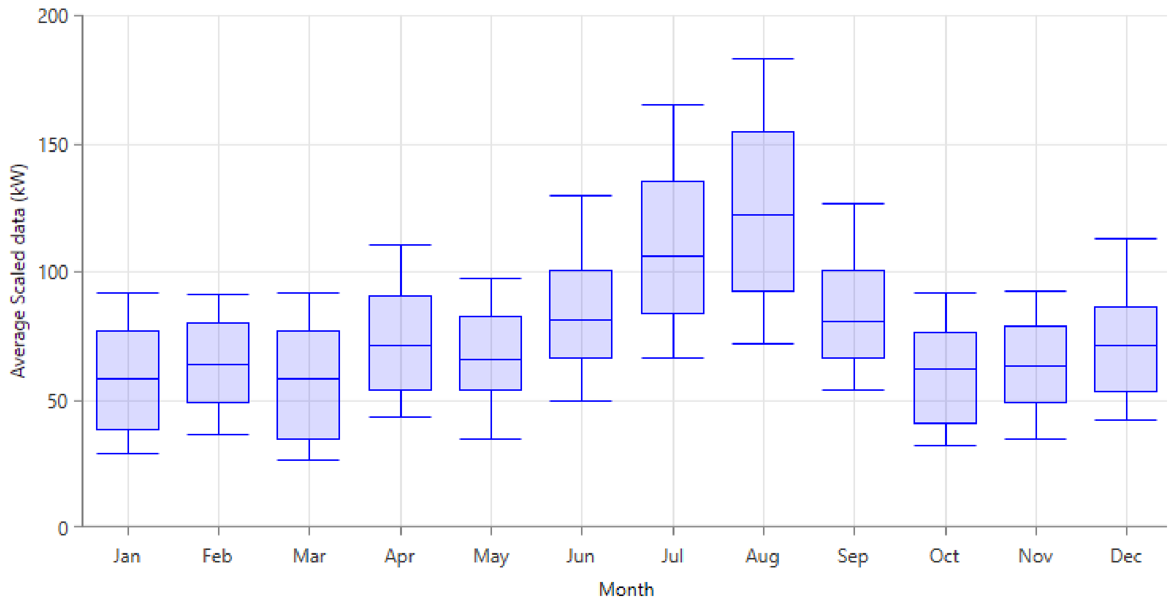

Figure 21: Seasonal Load Profile of Donousa by HOMER

Figure 21 above, presents the seasonal demand profile of the island after importing the data of the electricity demand of Donousa to HOMER Pro. The annual average electric demand of the island is 1,814kWh/day with a random day-to-day variability set to 10%. From this figure it is observed that during the summer period (from June until September) the demand shows a notable increase because of the large number of tourists, while the other period of time it is relatively lower. Thus, the rise of the population of the island in combination with the high temperature in summer, results to higher electricity consumption, mainly due to the utilization of air-conditioning systems in the households and hotels.

Moreover, it can be seen that in February the energy demand in is slightly higher than January and March due to the fact that the temperature this month is lower (Figure 22) and the residents consume more energy in order to cover their heat requirements. Moreover, in April the energy demand is again relatively higher than March and May because of the Easter celebration in Greece which last 2 weeks. During this period the population of the island rises because of the arrival of the relatives of the inhabitants, who visit the island in order to spend these days with their family (SOUTH AEGEAN REGION, 2014). Similarly, during the Christmas vacations in December the population of the island rises again, because of the arrival of the relatives of its residents and alongside the lower temperature the energy demand is increasing .Finally, besides April, December and the period of tourism the peak load of the island for all the other months is under 100kW. The hourly load profile of the island for all the months is illustrated in APENDIX 1: Hourly Demand Profile of Donousa.

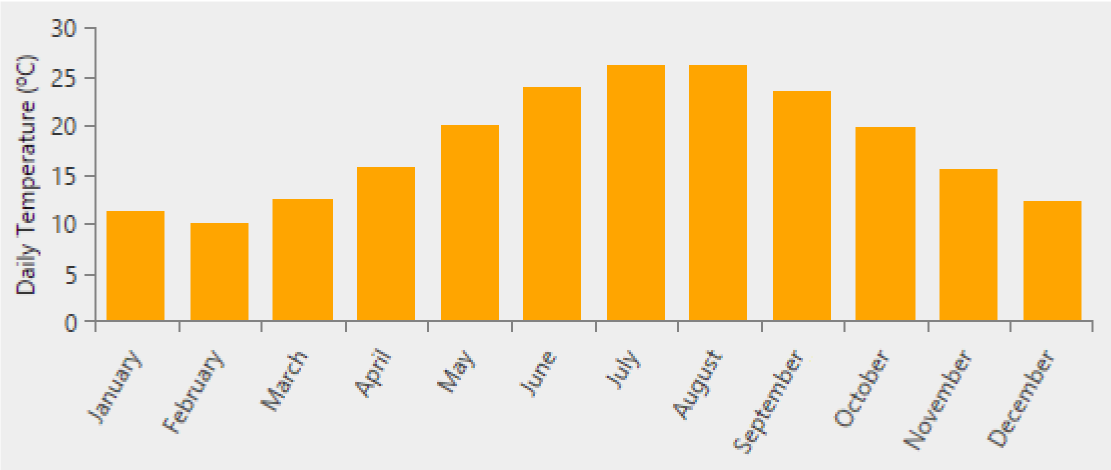

Figure 22: Average temperature of Donousa per month by HOMER

3.3 Components and parameters of the Hybrid Energy System

Donousa is one of the 32 Aegean off-grid islands that are powered by oil-based power units and specifically diesel generators. It possess a 210kW diesel engine and its cost of electricity is 0.636€ and the current price of diesel in Greece is 1.4€/L (GREEK ECONOMY, 2017).

The components that were used for the modelling of the Hybrid Energy System are:

- Diesel Generator
- PV panels
- Wind Turbines
- Batteries (Lead Acid, Vanadium, Lithium-Ion)
- Converter

The cost, the number of each unit used, the hours of operation, etc. need to be mentioned for the simulation of HOMER program.

3.3.1 PV Panels

For the modelling of PVs, a generic flat plate PV has been selected with a lifetime of 20 years. The initial capital and replacement cost of the PV, are set to 1250€/kW, while its operation and maintenance cost is set to 10€/kW (IRENA, 2018). Table 4 summarizes some characteristics of the generic flat plate panel.

Rated Capacity (kW)	500
Temperature Coefficient	-0.05
Operating Temperature (^oC)	47
Efficiency (%)	13
Derating Factor (%)	80
Ground Reflectance (%)	20

Table 4: PV Characteristics

It should be mentioned that for all the simulations of the different hybrid energy systems scenarios, the size of the PVs is optimized by HOMER.

3.3.2 Wind Turbines

In the various simulations of hybrid systems, AC type wind turbines have been used and specifically the Northern Power NPS100C-21, with a rated capacity of 100kW and a lifetime of 20 years. The initial capital and replacement costs of 1 NPS100C-21 turbine, are set to 130000€, while its operation and maintenance cost is set to 1300€/kW (IRENA, 2018). In Figure 23 below the power curve of the wind turbine is presented.

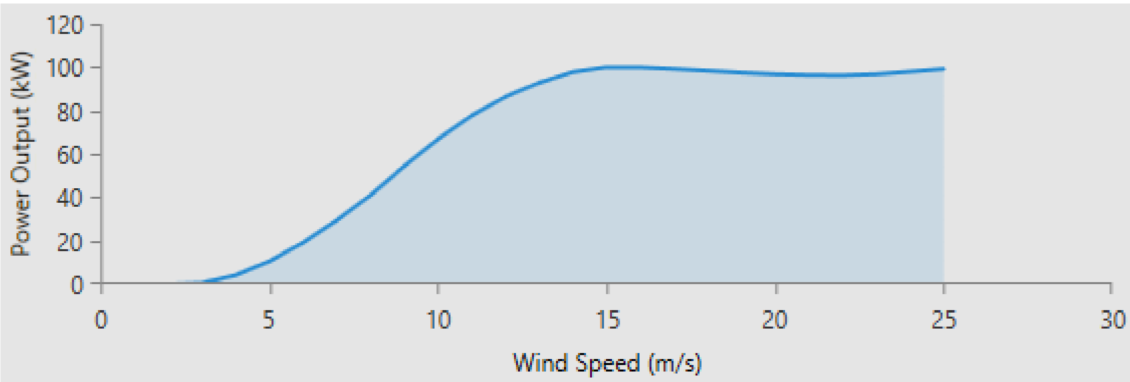

Figure 23: Wind Turbine Power Curve

It should be mentioned that, for every scenario of the examined hybrid energy systems the number of the wind turbines is optimized by HOMER.

3.3.3 Diesel Generator

For the modelling part of the diesel engine, it has been selected a Generic Medium generator. HOMER gives the option of sizing its capacity manually. For all the simulations and scenarios analysed in this software the size of the diesel generator is set stable at 150kW, with a lifetime of 15,000 hours and it has a 25% minimum load ratio.

Its initial capital and replacement costs are set to 430€, while its operation and maintenance cost is set to 0.03€/hour (LAZARD, 2017).

The fuel type of the generator is diesel and its price is set to 1.4€/L, which is the current price of diesel fuel in Greece. Figure 24 illustrates the fuel curve of selected diesel generator for HOMER simulations.

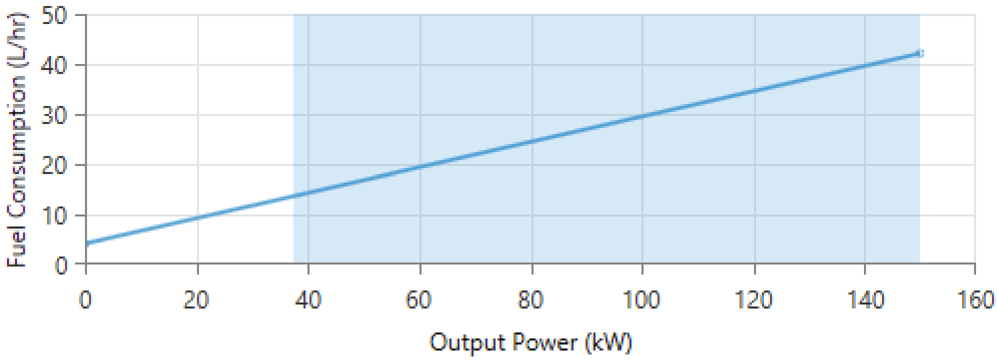

Figure 24: Fuel curve of the diesel generator

3.3.4 Converter

For the simulations of the hybrid energy systems, HOMER offers the choice of its generic system converter which has been chosen. Its initial capital and replacement costs are set to 300€, its lifetime to 15 years and its efficiency is 95%. For all the examined scenarios the size of the converter is optimized by HOMER.

3.3.5 Batteries

The different combination of hybrid energy systems will be examined for 3 different types of batteries (Lead Acid, Lithium Ion and Vanadium Flow).

a) <u>Vanadium Flow Battery</u>

For this type of electrochemical device, the redT 30kW-150kWh Battery has been selected with a 25 years lifetime (redT Energy Storage, 2017). Its initial capital and replacement costs are set at 400€/kWh and for the total technology 60,000€, while its operation and maintenance cost is set at 8€/kWh/year or 1200€/year (US TRADE AND DEVELOPMENT AGENCY, 2017). This battery is a 20ft Hi-Cube Container and its dimensions are: 6.058m x 2.438m x 2.896m (redT Energy Storage, 2017). The characteristics of this battery, which can be found on HOMER database, are described in Table 5 below.

Nominal Voltage (V)	96
Nominal Capacity (kWh)	150
Nominal Capacity (Ah)	1.56E + 0.3
Roundtrip efficiency (%)	75
Minimum State of Charge (%)	0%
Maximum Charge Current (A)	208
Maximum Discharge Current (A)	208
Throughput (kWh)	876,000

Table 5: Redt 30kW-150kWh characteristics

b) Lithium-Ion Battery

For this type of electrochemical device, the NEC DSS 170kWh 369kW battery has been selected and its lifetime is set at 15 years (Ting Guan, 2014). Its initial capital and replacement costs are set at 700€/kWh and for the total technology 119,000€, while its operation and maintenance cost is very low and set at 11€/year (US TRADE AND DEVELOPMENT AGENCY, 2017) (Suratsawadee Anuphappharadorn, 2014). The dimensions of this battery are: 1.683m x 2.037m x 2.492m (NEC Energy Solutions, 2018). Its characteristics, which can be found on HOMER database, are described in Table 6 below.

Nominal Voltage (V)	720
Nominal Capacity (kWh)	170
Nominal Capacity (Ah)	236
Roundtrip efficiency (%)	96
Minimum State of Charge (%)	0%
Maximum Charge Current (A)	628
Maximum Discharge Current (A)	628
Throughput (kWh)	849,996

Table 6: NEC DSS 170kWh 369kW battery characteristics

c) Lead Acid Battery

For this type of electrochemical device, the Hoppecke 24 OPzS 3000 battery has been selected and its lifetime is 18 years (HOPPECKE, 2017). Its initial capital and replacement costs are set at 168€/kWh and 157€/kWh respectively. The total capital and replacement cost of the technology is 1201€ and 1123€ respectively, while its operation and maintenance cost is set at 12€/year (US TRADE AND DEVELOPMENT AGENCY, 2017) (Suratsawadee Anuphappharadorn, 2014). The dimensions of this battery are: 0.215m x 0.580m x 0.815m (HOPPECKE, 2017). Its characteristics, which can be found on HOMER database, are described in Table 7 below.

Nominal Voltage (V)	2
Nominal Capacity (kWh)	7.15
Nominal Capacity (Ah)	3.57E + 0.3
Roundtrip efficiency (%)	86
Minimum State of Charge (%)	30%
Maximum Charge Current (A)	610
Maximum Discharge Current (A)	610
Throughput (kWh)	10,118.3

Table 7: Characteristics of Hoppecke 24 OPzS 3000

3.3.6 Other Input parameters

The lifetime of the project is set at 20 years. The nominal discount rate and the expected inflation rate are set at 6% and 2% respectively, while the real discount rate is calculated at 3.92%.

3.4 Modelling scenarios of Hybrid Energy Systems

For the simulations in HOMER 4 different combinations of Hybrid Energy Systems were selected. These are:

- PVs-Diesel Generator + Storage
- Wind Turbines-Diesel Generator + Storage
- Wind Turbines-PVs-Diesel Generator + Storage
- Wind Turbines-PVs + Storage

In order to assess these scenarios in more depth, 3 different types of batteries will be implemented in the simulation process. These are: Lead-Acid, Vanadium Flow and Lithium-Ion.

The energy strategy that has been decided in all the scenarios that combine renewable energy sources and diesel generator is the Load Following Strategy of HOMER. According to this, the diesel power unit starts to operate when the other energy sources (renewables) and the batteries are unable to cover the demand.

3.4.1 PV-Diesel Generator Hybrid Energy System

In this scenario the photovoltaic panels provide the required power to the load through the power converter. The additional energy from photovoltaics charges the batteries until they reach their maximum charge level. The main purpose of using batteries is to supply or store energy according to demand. The diesel generator starts to operate if the demand for the load cannot be covered by the photovoltaic panels and the batteries. The main energy elements of the PV-diesel hybrid system are photovoltaic panels, a diesel generator, batteries and an energy converter. The size of the generator is set at 150kW, while the size of the PVs and the converter alongside the number of the batteries were optimized by HOMER, in order to provide us the solution with the lowest NPC.

3.4.2 Wind Turbines-Diesel Generator Hybrid Energy System

This hybrid system that was studied through simulations in HOMER, is a combination of a diesel generator, batteries wind turbines. The size of the generator is set at 150kW, while the number of the wind turbines and the batteries alongside the size of the converter were optimized by HOMER, in order to provide us the combination with the lowest NPC. In this scenario the operation of the hybrid system is as it follows: The wind turbine covers the load and the extra energy produced (above average hourly-daily demand), charges the batteries until they are fully charged. The purpose of the batteries is to give or store energy according to the necessities of demand. If the batteries are fully charged and the wind turbine continues to operate, excess electricity occurs. The diesel backup system starts to operate when the batteries are empty and the wind potential at that time is unable to cover the load.

3.4.3 Wind Turbines-PVs-Diesel Generator

This hybrid system is a combination of a diesel generator, PVs, wind turbines and batteries. The size of the generator is set at 150kW, while the number of the wind turbines and the batteries alongside the size of the converter and PVs were optimized by HOMER, in order to provide us the combination with the lowest NPC. In this scenario the photovoltaic panels and the wind turbine provide the required power to the load through the power converter. The additional energy charges the batteries until they reach their maximum charge level. The main purpose of using storage is to supply or store energy according to demand. The diesel generator starts to operate if the demand for the load cannot be covered by the photovoltaic panels, the wind turbines and the batteries.

3.4.4 PVs-Wind Turbines

The pollutants of the systems with diesel generator resulted to a simulation of a hybrid system consisting only of renewable energy sources. Specifically, this system exploits solar radiation and wind energy using wind turbines and photovoltaic panels. In this scenario, the size of the PVs and the converter, alongside the number of wind turbines and batteries were optimized by HOMER in order to provide a reliable combination that covers the energy requirements of the island in the most cost effective way (lowest NPC).

During the performance of this energy system the next cases can occur:

- If the demand for electricity is less than the energy generated by the wind turbine and the photovoltaics, the surplus energy produced by these 2 energy sources is stored on the batteries.
- If the demand is higher than the energy generated by the wind turbine, then the energy deficit is covered by the photovoltaic cells. If the load cannot even covered by the photovoltaic generation, then the energy of the charged batteries will cover the deficit.

Regarding the battery charging, it should be mentioned that in both cases when the battery capacity reaches the upper or lower permissible charge limit, the control system pauses the charging or discharging of the batteries respectively.

3.5 Summary

In this chapter there has been an assessment of various software tools related to energy modelling and it was found that for the case of this project, HOMER is the most suitable. Afterwards, a detailed description of this program and of its basic functions (simulation, optimization and sensitivity analysis) alongside its economic features and limitations followed, in order to comprehend its operation.

Furthermore, after the acquisition of the hourly the load profile of the island from a previous project and its weather characteristics (solar radiation, wind speed and temperature) the input data of the components of the HES were presented and finally the modelling scenarios of the simulations were discussed.

4 RESULTS

In this section the results of the simulations in HOMER are presented and discussed. It should be mentioned that 4 different combinations were analysed, each one with 3 different types of battery. During the assessment of the results, it was decided to investigate them according to their cost, energy performance and emissions.

One of the most important parameters of HOMER is Net Present Cost (NPC) of the investment. It is defined as the difference between the present value of the costs of installation and operation of the HES over its lifetime and the present value of all the incomes of the project during its lifetime. Furthermore, another notable factor that will be taken into consideration for the financial evaluation of the results is the cost of electricity (COE), which is the average cost of useful electricity per kWh, generated by the energy system.

Regarding the energy performance of the system, there are 2 significant factors that determine it. Initially, the renewable energy fraction (R.F) which expresses the fraction of the renewable energy delivered to the demand. In addition, the excess electricity (E.E) which is defined as the additional electrical energy produced by the system and cannot be used to cover the demand or charge the batteries. Finally, the last factor that will be analysed is the emissions that produced from the operation of the diesel generator. Lower values of pollutants mean a more suitable energy solution for the island.

4.1 Initial System

Before the implementation and modelling of the different energy scenarios and their results discussion it was necessary to simulate the initial energy situation of the island. An auto-sizing generator was selected and after HOMER optimization it was set at 210kW.

HOMER estimated that the total NPC of this system is 5,628,895.42€, with a COE of 0.619€ which is pretty close to the actual current COE of Donousa which is 0.636€. In addition, the generator in this case consumes 214,679L of diesel per year and produces 669,863kWh/year.

Figure 25 illustrates the total cost of the system over the 20 years of its lifetime. The cost for each part of the system is divided into the main economic characteristics of the

Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system is the cost of the fuel of the diesel generator which is enormous (comparing to its installation, replacement and operation & maintenance cost), confirming that this is a major drawback of this power generation technology.

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Autosize Genset	€90,300.00	€683,638.03	€755,258.91	€4,113,086.73	(€13,388.25)	€5,628,895.42
System	€90,300.00	€683,638.03	€755,258.91	€4,113,086.73	(€13,388.25)	€5,628,895.42

Figure 25: Cost Summary of initial System by HOMER

This system produces 561,946kg/year of CO_2, which is enormous due to the fact that its only power source is the diesel generator.

4.2 Combinations of Hybrid Energy Systems with lead-acid battery

4.2.1 PV-Diesel Generator System

The diagram of the PV-Diesel Generator with lead acid battery system in HOMER is illustrated in Figure 26.

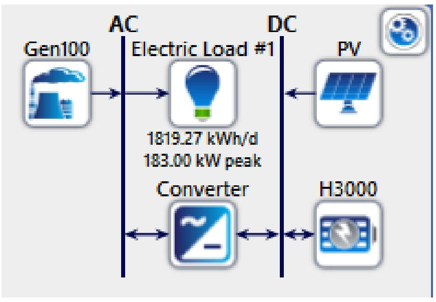

Figure 26: PV-Diesel Generator with lead acid battery

After the optimization of HOMER the components of the most cost optimal combination of the PV-Diesel Generator (lead acid) system are: 622kW of PVs, a diesel generator of 150kW, a storage bank of 3,117kWh and a converter of 181kW.

HOMER estimated that the total NPC of this system is *2,143,546€*, with a COE of *0.236€.* In addition the diesel generator in this case consumes 13,314L of diesel per year. The energy performance of this system is presented in Table 8 below.

PVs electricity production (kWh/year)	931,356 (95.9%)
Diesel Generator electricity production (kWh/year)	40,305 (4.1%)
Total electricity production (kWh/year)	971,661
AC Primary Load (kWh/year)	664,034
Excess Electricity (kWh/year)	219,527 (22.6%)
Renewable Fraction (%)	93.9%
Unmet Electric Load (kWh/year)	0
Capacity Shortage (kWh/year)	0

Table 8: Energy Performance of PV-Diesel (lead acid) System

According to the simulation results, the system produces 971,661kWh/year of electricity, of which 95.9% comes from the photovoltaic array. From the generated energy the system consumes 664,034kWh/year. An excess electricity of 22.6% is observed, which occurs from the energy production from PVs when the load is covered and the batteries are fully charged. From the above table it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability. Additionally, the diesel engine produces only 4.1% of the total generated electricity, and so the system acquires a very large fraction of renewable energy at 93.9%.

Figure 27 below presents the average monthly electricity generation and the percentages of its cover by the photovoltaic panels and the diesel generator.

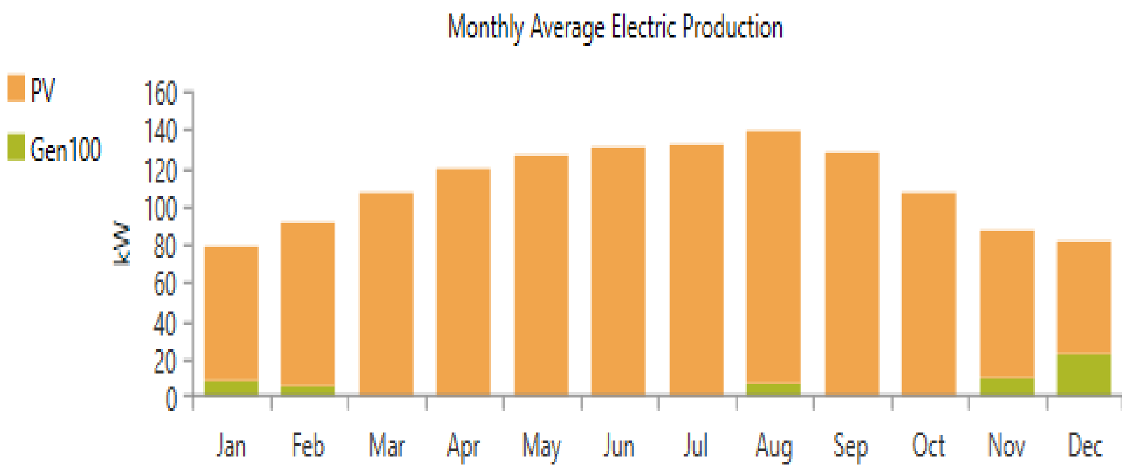

Figure 27: Monthly average electricity production from PV-Diesel system (lead acid)

From this figure, it is observed that the contribution of the generator to the electricity supply is minimized and thus, the high fraction of renewable energy occurs. The generator is mainly used in August, despite the high radiation values of the month, as the energy needs of the island are very high due to tourism. Furthermore, a notable use of the diesel engine can be seen from November to February, where there are the lowest rates of solar radiation during the year.

The following Table 9 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation of photovoltaic panels and for the installation and replacement of the batteries. It is also notable that while the cost of installing the diesel generator is low, the cost of its fuel is enormous (comparing to its installation cost), confirming that this is a major drawback of this power generation technology given the fact that it has a low power supply.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	777,606.22	0	85,133.58	0	0	862,739.80
Generic Generator	64,500	0	45,694.89	255,080.52	(318.77)	364,956.64
Hoppecke 24 OPzS 3000	523,636	313,892.25	71,600.98	0	(61,162.48)	847,966.74
System Converter	54,189.56	30,431.98	0	0	(16,738.27)	67,833.28
System	1,149,931.78	344,324.23	202,429.45	255,080.52	(78,219.52)	2,143,546.46

Table 9: Cost Summary of PV-Diesel (lead acid) System

It is observed that, while the fraction of renewable energy is large (93.9%), the cost of the generator remains high despite the fact that it has a small share, since it is activated only when PV generation and batteries are insufficient to cover the load. This is because the diesel engine has high power output and consequently high fuel consumption. Moreover, the average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.236€, which is much lower than the current cost of electricity of Donousa (0.636€).

The reduced fuel consumption and operation of the diesel engine due to the high penetration of PVs and batteries in this system has led to a heavily decreased production of CO_2 emissions, about 34,823kg/year, which is extremely lower than the 561,946kg/year of the initial system.

4.2.2 Wind-Diesel Generator System

The diagram of the Wind-Diesel Generator with lead acid battery system in HOMER is illustrated in Figure 28.

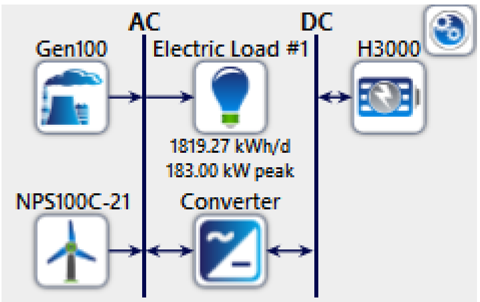

Figure 28: Wind-Diesel Generator System with lead acid battery

After the optimization of HOMER the components of the most cost optimal combination of the Wind-Diesel Generator (lead acid) system are: 6 wind turbines of 100kW each, a diesel generator of 150kW, a storage bank of 2,560kWh and a converter of 189kW.

HOMER estimated that the total NPC of this system is *1,983,803€*, with a COE of *0.218€*. In addition the diesel generator in this case consumes 19,270L of diesel per year. The energy performance of this system is presented in Table 10 below.

Wind turbines electricity production (kWh/year)	1,195,247 (95.1%)
Diesel Generator electricity production (kWh/year)	60,926 (4.85%)
Total electricity production (kWh/year)	1,256,173
AC Primary Load (kWh/year)	663,863
Excess Electricity (kWh/year)	541,182 (43.1%)
Renewable Fraction (%)	90.8%
Unmet Electric Load (kWh/year)	171 (0.02%)
Capacity Shortage (kWh/year)	619 (0.09%)

Table 10: Energy Performance of Wind-Diesel (lead acid) System

According to the simulation results, the system produces 1,256,173kWh/year of electricity, of which 95.1% comes from the wind turbines. From the generated energy the system consumes 663,863kWh/year. An excess electricity of 43.1% is observed, which occurs from the energy production from wind turbines when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is extremely low at 0.02%. Additionally, the diesel engine produces only 4.85% of the total generated electricity, and so the system acquires a very large fraction of renewable energy at 90.8%.

Figure 29 below presents the average monthly electricity generation and the percentages of its cover by the wind turbines and the diesel generator.

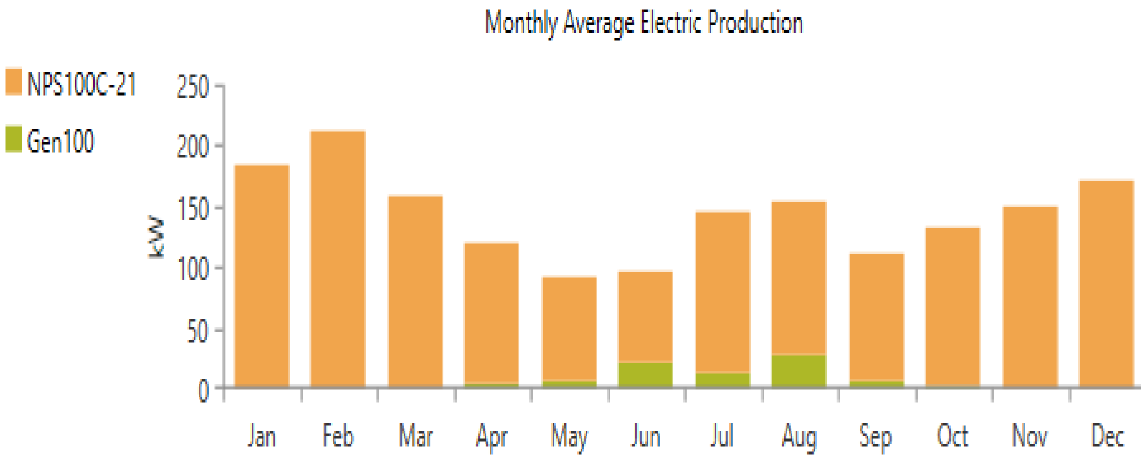

Figure 29: Monthly Average Energy Production of Wind-Diesel Generator (lead acid) System

From this figure, it is observed that the contribution of the generator to the electricity supply is low and thus, the high fraction of renewable energy occurs. The generator is mainly used in summer months, because of the high energy demand due to tourists and the lower rates of average wind speeds in summer. Furthermore, from November until March the diesel engine power supply is negligible due to the high wind speeds, which result to high generation of electricity from wind turbines. This reason also justifies the high excess electricity of the system (43.1%), especially in winter months where the energy demand requirements are low and the electricity supply high due to the high wind potential of the region.

Table 11 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation of wind turbines. It is also notable that, while the cost of installing the diesel generator is low, the cost of its fuel is enormous (comparing to its installation cost), confirming that this is a major drawback of this power generation technology given the fact that it has a low power supply. Another disadvantage of this system is the high cost of the installation and replacement of the batteries, which are unable to exploit a significant amount of surplus electricity produced by the wind turbines.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Northern Power NPS100C-21 WT	780,000	0	106,744.57	0	0	886,744.57
Generic Generator	64,500	34,402.57	56,533.57	369,196.86	(23,190.36)	525,614.44
Hoppecke 24 OPzS 3000	429,958	201,297.75	58,791.63	0	(165,413.13)	524,614.44
System Converter	56,678.43	31,829.69	0	0	(17,507.04)	71,001.08
System	1,331,136.43	267,510.20	222,069.77	369,196.86	(206,110.54)	1,983,802.73

Table 11: Cost Summary of Wind-Diesel (lead acid) System

It is observed that, while the fraction of renewable energy is large (90.8%), the cost of the generator remains high despite the fact that it has a small share, since it is activated only when wind generation and batteries are insufficient to cover the load. This is because the diesel engine has high power output and consequently high fuel consumption. Furthermore, its limited lifetime (15,000 hours) requires its replacement during this 20 years period. The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.218€, which is much lower than the current cost of electricity of Donousa (0.636€).

The reduced fuel consumption and operation of the diesel engine due to the high penetration of wind turbines and batteries in this system has led to a heavily decreased production of CO2 emissions, about 50,402kg/year, which is extremely lower than the 561,946kg/year of the initial system.

4.2.3 Wind-PV-Diesel Generator (lead acid) System

The diagram of the Wind-PV-Diesel Generator with lead acid battery system in HOMER is illustrated in Figure 30.

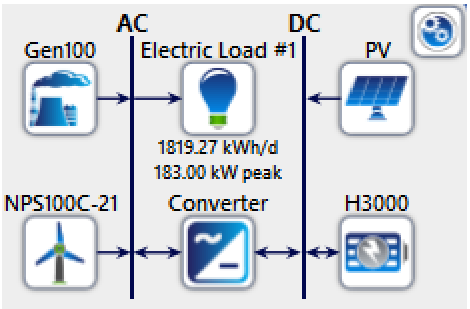

Figure 30: Wind-PV-Diesel Generator System with lead acid battery

After the optimization of HOMER the components of the most cost optimal combination of the Wind-Diesel Generator (lead acid) system are: 3 wind turbines of 100kW each, 276kW of PVs, a diesel generator of 150kW, a storage bank of 2,309kWh and a converter of 152kW.

HOMER estimated that the total NPC of this system is *1,634,874€*, with a COE of *0.180€*. In addition the diesel generator in this case consumes 7,509L of diesel per year. The energy performance of this system is presented in Table 12 below.

PVs electricity production (kWh/year)	413,958 (40%)
Wind turbines electricity production (kWh/year)	597,623 (57.7%)
Diesel Generator electricity production (kWh/year)	23,304 (2.25%)
Total electricity production (kWh/year)	1,034,885
AC Primary Load (kWh/year)	664,007
Excess Electricity (kWh/year)	319,898 (30.9%)
Renewable Fraction (%)	96.5%
Unmet Electric Load (kWh/year)	27.0 (0.004%)
Capacity Shortage (kWh/year)	150 (0.02%)

Table 12: Energy Performance of Wind-PV-Diesel Generator (lead acid) System

According to the simulation results, the system produces 1,034,885kWh/year of electricity, of which 57.7% comes from the wind turbines and 40% from PVs. From the generated energy the system consumes 664,007kWh/year. An excess electricity of 30.9% is observed, which occurs from the energy production from wind turbines and photovoltaics when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is negligible at 0.004%. Additionally, 97.7% of the total generated electricity comes from the wind turbines and the PVs and only 2.25% from the diesel engine, and so the system acquires a very large renewable energy fraction at 96.5%.

Figure 31 presents the average monthly electricity generation and the percentages of its cover by the wind turbines, PVs and the diesel generator. From this figure, it is observed that the contribution of the generator to the electricity supply is minimized. It is mainly used in summer months (especially in August), because of the high energy demand due to tourists arrival. Furthermore, all the other months of the year the diesel's engine power supply is negligible due to the high wind speeds (especially in winter), which result to high generation of electricity from wind turbines. This reason also justifies the notable rate of excess electricity of the system which is 30.9% and considering that wind and solar energy rely on weather conditions the value of the excess electricity is normal. One noteworthy advantage of this system is that it acquires a very high renewable fraction due to the fact that the solar and wind power complement each other during the year. For instance, during winter the PVs power output is lower because of the lower percentages of solar radiation, while the power output of wind turbines is higher because of the high wind velocities during this period. On the other hand during summer months the wind velocities rates are decreasing and consequently the power output of the wind turbines, but due to the higher solar radiation of this time-period the power output of PVs is increasing.

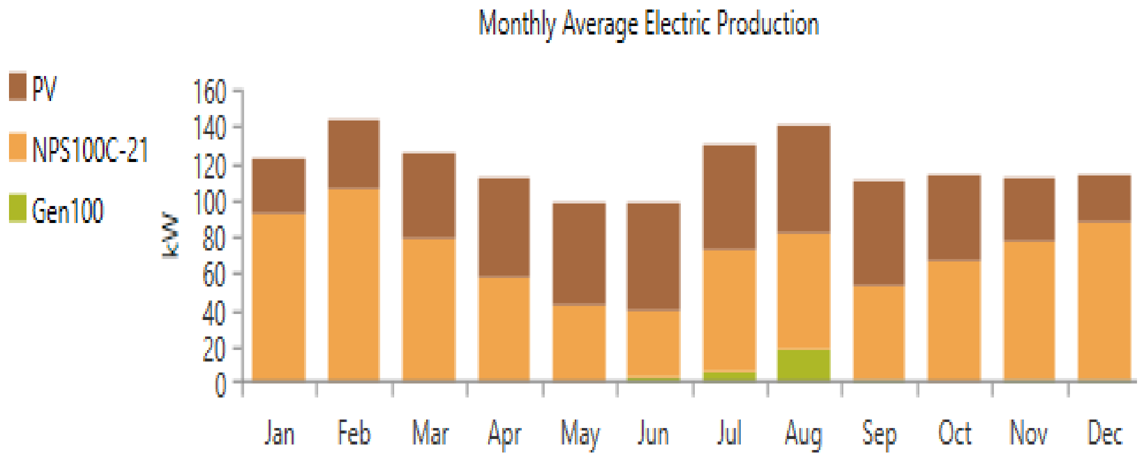

Figure 31: Monthly Average Electric Production from Wind-PV-Diesel (lead acid) System

Table 13 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation and replacement of the batteries and the installation of wind turbines and photovoltaics. It is also notable that, while the cost of installing the diesel generator is low, the cost of its fuel is more than double comparing to its installation cost.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	345,621.04	0	37,839.15	0	0	383,460.18
Northern Power NPS100C-21 WT	390,000	0	53,372.29	0	0	443,372.29
Generic Generator	64,500	0	23,648.03	143,863.18	(14,583.63)	217,427.58
Hoppecke 24 OPzS 3000	387,923	203,982.99	53,043.84	0	(111,505.84)	533,443.99
System Converter	45,637.43	25,629.24	0	0	(14,096.65)	57,170.02
System	1,233,681.46	229,612.23	167,903.31	143,863.18	(140,186.13)	1,634,874.06

Table 13: Cost Summary of Wind-PV-Diesel Generator (lead acid) System

The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.180€, which is much lower than the current cost of electricity of Donousa (0.636€).

The reduced fuel consumption and operation of the diesel engine due to the high penetration of wind turbines, PVs and the utilization of batteries in this system has led to a heavily decreased production of CO2 emissions, about 19,640kg/year, which is extremely lower than the 561,946kg/year of the initial system.

4.2.4 Wind-PV (lead acid) System

The diagram of the Wind-PV with lead acid battery system in HOMER is illustrated in Figure 32 below.

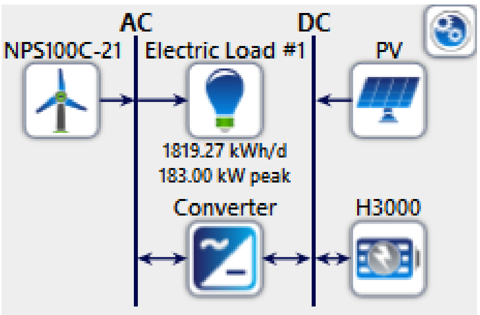

Figure 32: Wind-PV System with lead acid battery

After the optimization of HOMER the components of the most cost optimal combination of the Wind-Diesel Generator (lead acid) system are: 3 wind turbines of 100kW each, 523kW of PVs, a storage bank of 3,532kWh and a converter of 200kW.

HOMER estimated that the total NPC of this system is *1,967,127*€, with a COE of *0.217*€. The energy performance of this system is presented in Table 14 below.

PVs electricity production (kWh/year)	782,893 (56.7%)
Wind turbines electricity production (kWh/year)	597,623 (43.3%)
Total electricity production (kWh/year)	1,380,517
AC Primary Load (kWh/year)	663,681
Excess Electricity (kWh/year)	664,306 (48.1%)
Renewable Fraction (%)	100%
Unmet Electric Load (kWh/year)	353 (0.05%)
Capacity Shortage (kWh/year)	661 (0.09%)

Table 14: Energy Performance of Wind-PV (lead acid) System

According to the simulation results, the system produces 1,380,517kWh/year of electricity, of which 43.3% comes from the wind turbines and 56.7% from PVs. From the generated energy the system consumes 663,681kWh/year. An excess electricity of 48.1% is observed, which occurs from the energy production from wind turbines and photovoltaics when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is negligible at 0.05%.

Figure 33 presents the average monthly electricity generation and the percentages of its cover by the wind turbines and PVs.

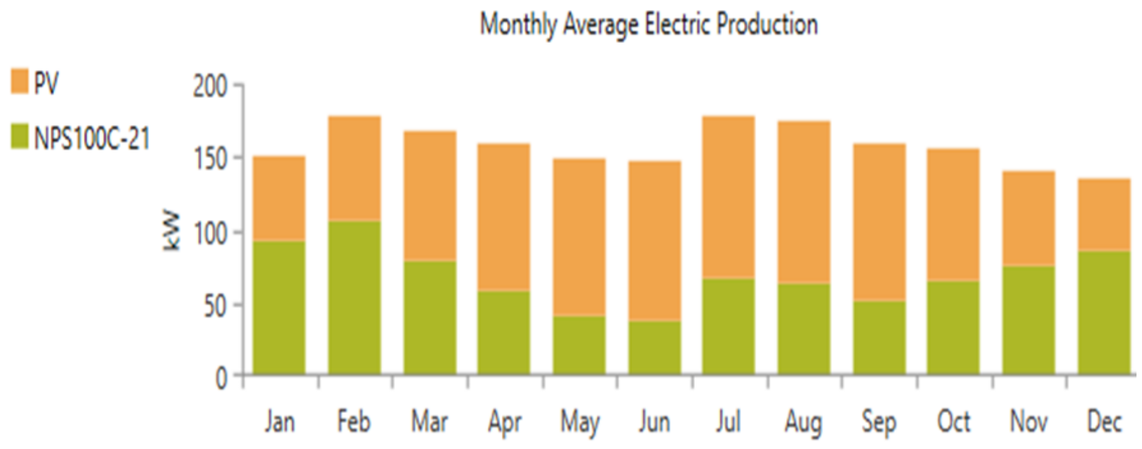

Figure 33: Monthly Electricity Production of Wind-PV (lead acid) System

From this figure, it is observed that the contribution of PVs in the electricity generation of the system is higher than the wind turbines. Moreover, the solar and wind power complement each other during the year. Specifically, during winter the PVs power output is lower because of the lower percentages of solar radiation, while the power output of wind turbines is higher because of the high wind velocities during this period. On the other hand during a 7th month period (between April and October)the wind velocities rates are decreasing and consequently the power output of the wind turbines, but due to the higher solar radiation of this period the power output of PVs is increasing. The percentage of the excess electricity of this system is very high (48.1%), due to the fact that the system in order to cover constantly its load, relies only in renewable energy sources whose main characteristic is the unstable and unpredictable power generation and consequently batteries are unable to store all the excess electricity.

Table 15 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation photovoltaics and for the installation and replacement of the batteries and this fact indicates the importance of storage in off-grid systems that rely only in renewable energy sources. Additionally, the NPC of this system is slightly lower than some other systems that combine renewables and diesel power generation (PV-Diesel, Wind-Diesel) because the absence of diesel engine and fuel imports reduces the initial cost although it creates the need of extra renewable energy generation and storage.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	653,652.11	0	71,562.89	0	0	725,214.99
Northern Power NPS100C-21 WT	390,000	0	53,372.29	0	0	443,372.29
Hoppecke 24 OPzS 3000	593,294	277,590.26	81,125.88	0	(228,475.86)	723,534.28
System Converter	59,874.85	33,624.75	0	0	(18,494.36)	75,005.24
System	1,696,820.96	311,215.01	206,061.05	0	246,970.22	1,967,126.80

Table 15: Cost Summary of Wind-PV (lead acid) System

The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.217€, which is much lower than the current cost of electricity of Donousa (0.636€).

A noteworthy advantage is that due to the exclusive use of renewable energy this system generates zero pollutants.

4.2.5 Overall comparison of the different Hybrid Energy Systems with lead acid battery and results discussion

Table 16 below summarizes the most important elements of the simulated systems with lead acid batteries. The most cost-optimal solution is the combination of wind turbines with photovoltaic and diesel generators (lowest NPC and COE). This is followed by the solution of photovoltaics with wind turbines, which is slightly more advantageous than the combination of wind and diesel generator. The combination of PVs with a diesel generator is the most expensive energy system.

The limited use of the diesel generator alongside the reduced number of batteries, are the factors which determine that the combination with the wind turbines PVs and diesel generator is the most cost-effective solution. At the same time this use of the generator, during the summer months with the high demand, prevents the installation of extra renewable power generation. Compared to the combination without the generator in the 2nd most advantageous position, it is observed that while the number of wind turbines is the same the Wind-PV-Diesel Generator system has 247kW of less PVs installations. This fact justifies the difference in cost and the smaller excess electricity. If Greece achieve its aim of connecting the off-grid islands of the Aegean Sea with the mainland's grid (a very optimistic aim given the current financial situation of the country) and export the excess electricity to the grid, or if it can be exploited by other means (for desalination purposes), then the PV-Wind system will be the most appropriate energy solution for the island.

Hybrid Energy Systems	PV-Diesel Generator	Wind-Diesel Generator	Wind-PV-Diesel Generator	Wind-PV
Total NPC (€)	2,143,546	1,983,803	**1,634,874**	1,967,127
COE (€)	0.236	0.218	**0.180**	0.217
Total Electricity Production (kWh/year)	971,661	1,256,173	1,034,385	1,380,517
Excess Electricity (kWh/year)	**219,527 (22.6%)**	541,182 (43.1%)	319,898 (30.9%)	664,306 (48.1%)
Total Fuel (L/year)	13,314	19,270	7,509	**0**
CO_2 emissions (Kg/year)	34,823	50,402	19,640	**0**
Selection	X	X	V	X

Table 16: Summarized Characteristics of Simulated Hybrid Energy Systems with lead acid battery

Continuing the results discussion about the Net Present Cost (NPC) and the cost of electricity per kWh (COE), it can be seen a notable cost difference between the other 2 combinations of PV-diesel and Wind-diesel generator. Despite the fact that, the diesel engine in the system with the wind turbines consumes 5,956 L/year more than the system with the PVs and its total cost is 160,657.8€ higher, the difference in the number of batteries determines the reason that the wind-diesel combination is cheaper. It has 78 batteries less and as a result its total battery cost is 323,352.3€ less than the PV-Diesel combination. However, the larger number of batteries offers some advantages to the PV-Diesel system and alongside the increased solar radiation of the island it ensures a reduced operation of the diesel generator that leads to 15,579 kg/year less CO_2

emissions. Furthermore, the fact that this system has large storage capacity and do not depend on wind power resulted to a decreased excess electricity by 321,655 kWh/year than the wind-diesel system.

In general terms, it is observed an increased surplus of energy in combinations using wind turbines. The fluctuations of wind potential in the area create problems for the reliability of those systems and the necessary over-dimensioning of the wind generation in order to fully cover the load causes higher percentages of excess electricity. Moreover, the most environmentally friendly systems are those that obtain the highest percentage of renewable energy sources penetration. Diesel generators are the main sources of environmental pollutants in these systems. The quantity of emissions depends on the use of the generator (specifically its size, operating hours and fuel consumption) and this is the reason that Wind-PV-Diesel combination has reduced emissions.

4.3 Combinations of Hybrid Energy Systems with Lithium-Ion battery

4.3.1 PV-Diesel Generator (lithium-ion) System

The diagram of the PV-Diesel Generator with lithium-ion battery system in HOMER is illustrated in Figure 34.

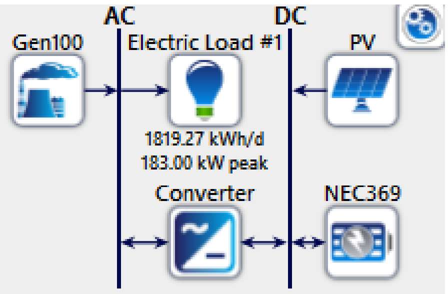

Figure 34: PV-Diesel Generator with lithium-ion battery

After the optimization of HOMER the components of the most cost optimal combination of the PV-Diesel Generator (lithium ion) system are: 569kW of PVs, a diesel generator of 150kW, a storage bank of 1,190kWh and a converter of 181kW. HOMER estimated that the total NPC of this system is *2,622,876€*, with a COE of *0.289€*. In addition, the diesel generator in this case consumes 27,301L of diesel per year. The energy performance of this system is presented in Table 17 below.

PVs electricity production (kWh/year)	851,921 (91.1%)
Diesel Generator electricity production (kWh/year)	83,423 (8.92%)
Total electricity production (kWh/year)	935,344
AC Primary Load (kWh/year)	664,034
Excess Electricity (kWh/year)	228,749 (24.5%)
Renewable Fraction (%)	87.4%
Unmet Electric Load (kWh/year)	0
Capacity Shortage (kWh/year)	0.386 (0.0001%)

Table 17: Energy Performance of PV-Diesel Generator (lithium-ion) System

According to the simulation results of HOMER, this system produces 935,344kWh/year of electricity, of which 91.1% comes from the photovoltaic array. From the generated energy the system consumes 664,034kWh/year. An excess electricity of 24.5% is observed, which occurs from the energy production from PVs when the load is covered and the batteries are fully charged. From the above table, it is obvious that the system fully covers the energy needs of the load of Donousa with high reliability. Additionally, the diesel engine produces 8.92% of the total generated electricity, and so the system acquires a large renewable energy fraction at 87.4%.

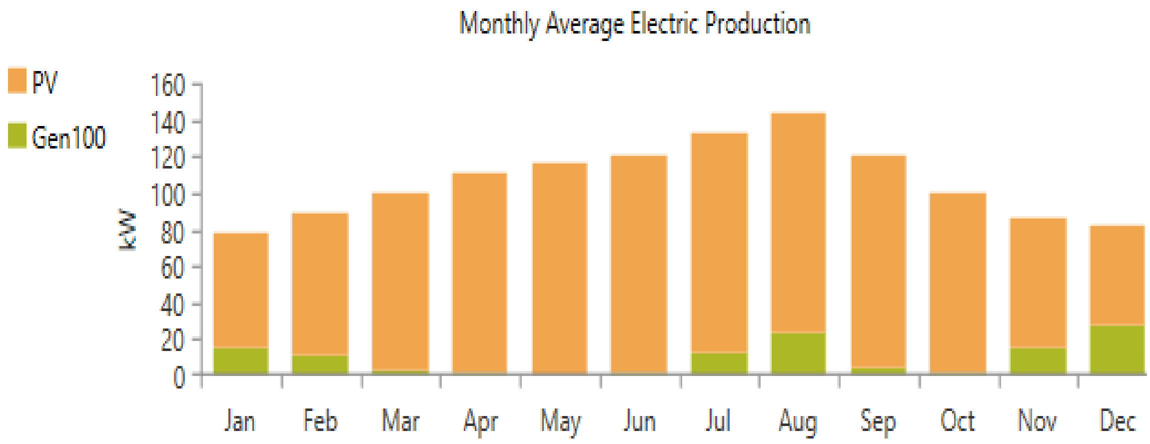

Figure 35: Monthly Average Electric Production of PV-Diesel (lithium-ion) System

Figure 35 above presents the average monthly electricity generation and the percentages of its cover by the photovoltaic panels and the diesel generator. It is observed that the diesel generator has a little contribution to the electricity supply and thus, the high fraction of renewable energy occurs. It is mainly used in August and July, despite the high radiation values of the month, as the energy needs of the island are very high due to tourism. Furthermore, a notable use of the diesel engine can be seen from November to February, where there are the lowest rates of solar radiation during the year.

Table 18 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation of batteries and photovoltaic panels. It is also notable that while the cost of installing the diesel generator is low, the cost of its fuel is enormous (comparing to its installation cost), confirming that this is a major drawback of this power generation technology given the fact that it has a low power supply.

It is observed that, while the fraction of renewable energy is large (87.4%), the cost of the generator remains high despite the fact that it has a small share, since it is activated only when PV generation and batteries are insufficient to cover the load. This is because the diesel engine has high power output and consequently high fuel consumption.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	711,284.87	0	77,872.62	0	0	789,157.48
Generic Generator	64,500	43,618.56	90,835.53	523,066.70	(996.15)	721,024.63
NEC DSS 170kWh 369kW	833,000	467,799.33	1,053.76	0	(257,300.05)	1,044,553.04
System Converter	54,397.71	30,547.19	0	0	(16,801.63)	68,140.27
System	1,663,179.58	541,965.08	169,761.90	523,066.70	(275,097.84)	2,622,875.43

Table 18: Cost Summary of PV-Diesel Generator (lithium-ion) System

Moreover, the average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.289€, which is much lower than the current cost of electricity of Donousa (0.636€).

The reduced fuel consumption and operation of the diesel engine due to the high penetration of PVs and batteries in this system has led to a heavily decreased production of CO_2 emissions, about 71,408kg/year, which is extremely lower than the 561,946kg/year of the initial system.

4.3.2 Wind-Diesel Generator (lithium-ion) System

The diagram of the Wind-Diesel Generator with lithium-ion battery system in HOMER is illustrated in Figure 36.

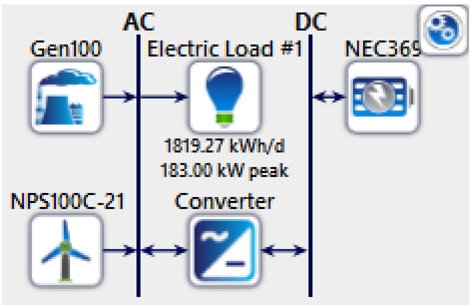

Figure 36: Wind-Diesel Generator with lithium-ion battery

After the optimization of HOMER the components of the most cost optimal combination of the Wind-Diesel Generator (lithium ion) system are: 7 wind turbines of 100kW each, a diesel generator of 150kW, a storage bank of 680kWh and a converter of 147kW.

HOMER estimated that the total NPC of this system is 2,447,614€, with a COE of 0.269€. In addition, the diesel generator in this case consumes 29,930L of diesel per year. The energy performance of this system is presented in Table 19 below.

Wind turbines electricity production (kWh/year)	1,394,454 (93.9%)
Diesel Generator electricity production (kWh/year)	91,295 (6.14%)
Total electricity production (kWh/year)	1,485,749
AC Primary Load (kWh/year)	663,850
Excess Electricity (kWh/year)	800,939 (53.9%)
Renewable Fraction (%)	86.2%
Unmet Electric Load (kWh/year)	184 (0.02%)
Capacity Shortage (kWh/year)	661 (0.09%)

Table 19: Energy performance of Wind-Diesel Generator (lithium-ion) System

According to the simulation results of HOMER, the system produces 1,485,749kWh/year of electricity, of which 93.9% comes from the wind turbines. From the generated energy the system consumes 663,850kWh/year. An excess electricity of 53.9% is observed, which occurs from the energy production from wind turbines when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is extremely low at 0.02%. Additionally, the diesel engine produces only 6.14% of the total generated electricity, and so the system acquires a fraction of renewable energy at 86.2%.

Figure 37 below presents the average monthly electricity generation and the percentages of its cover by the photovoltaic panels and the diesel generator.

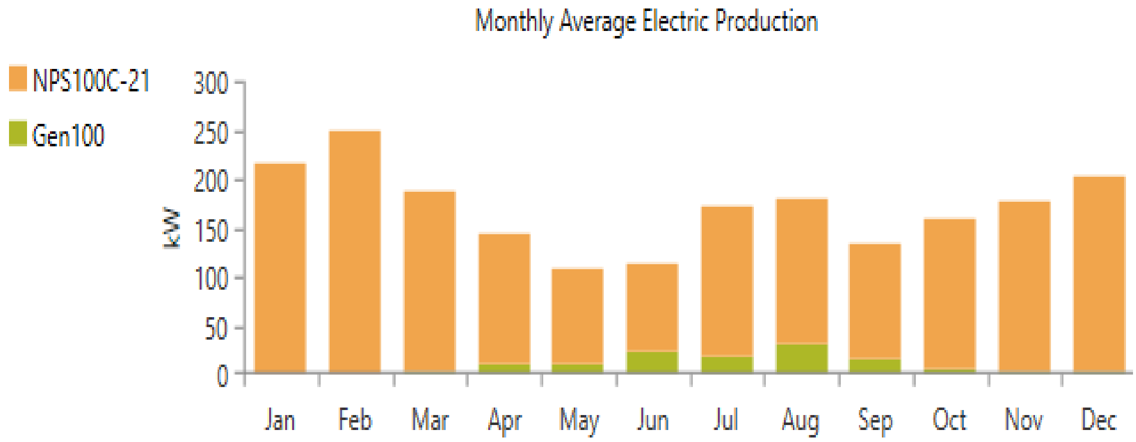

Figure 37: Monthly Average Electric Production of Wind-Diesel (lithium-ion) System

From this figure, it is observed that the contribution of the generator to the electricity supply is low and thus, the high fraction of renewable energy occurs. The generator is mainly used in summer months, because of the high energy demand due to tourists and the lower rates of average wind speeds in summer. Furthermore, from November until March the diesel engine power supply is negligible due to the high wind speeds, which result to high generation of electricity from wind turbines. This reason also justifies the high excess electricity of the system (53.9%), especially in winter months where the energy demand requirements are low and the electricity supply high due to the high wind potential of the region.

Table 20 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation of wind turbines. It is also notable that, while the cost of installing the diesel generator is low, the cost of its fuel is enormous (comparing to its installation cost), confirming that this is a major drawback of this power generation technology given the fact that it has a low power supply. Another disadvantage of this system is the high cost of the installation and replacement of the batteries, which are unable to exploit a significant amount of surplus electricity produced by the wind turbines.

It is observed that, while the fraction of renewable energy is large (86.2%), the cost of the generator remains high despite the fact that it has a small share, since it is activated only when wind generation and batteries are insufficient to cover the load. This is because the diesel engine has high power output and consequently high fuel consumption. Furthermore, its limited lifetime (15,000 hours) requires its replacement during this 20 years period. The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.269€, which is much lower than the current cost of electricity of Donousa (0.636€).

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Northern Power NPS100C-21 WT	910,000	0	124,535.34	0	0	1,034,535.34
Generic Generator	64,500	43,722.16	91,389.78	561,950.06	(637.54)	760,924.46
NEC DSS 170kWh 369kW	476,000	267,313.90	602.15	0	(147,028.60)	596,887.45
System Converter	44,117.62	24,755.74	0	0	(13,627.21)	55,266.15
System	1,494,617.62	335,811.81	216,527.26	561,950.06	(161,293.35)	2,447,613.40

Table 20: Cost Summary of Wind-Diesel (lithium-ion) System

The reduced fuel consumption and operation of the diesel engine due to the high penetration of wind turbines and batteries in this system has led to a heavily decreased production of CO2 emissions, about 76,717kg/year, which is extremely lower than the 561,946kg/year of the initial system.

4.3.3 Wind-PV-Diesel Generator (lithium-ion) System

The diagram of the Wind-Diesel Generator with lithium-ion battery system in HOMER is illustrated in Figure 38. After the optimization of HOMER the components of the most cost optimal combination of the Wind-PV-Diesel Generator (lithium ion) system are: 3 wind turbines of 100kW each, 283kW of PVs, a diesel generator of 150kW, a storage bank of 850kWh and a converter of 154kW.

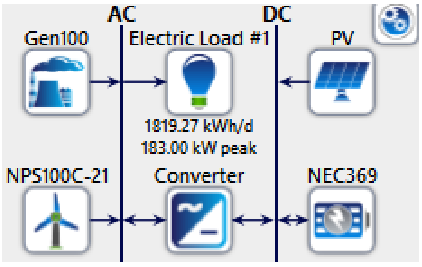

Figure 38: Wind-PV-Diesel Generator (lithium-ion) System

HOMER estimated that the total NPC of this system is *2,052,881€*, with a COE of *0.226€*. In addition, the diesel generator in this case consumes 15,104L of diesel per year. The energy performance of this system is presented in Table 21 below.

PVs electricity production (kWh/year)	424,155 (39.7%)
Wind turbines electricity production (kWh/year)	597,623 (56%)
Diesel Generator electricity production (kWh/year)	45,740 (4.28%)
Total electricity production (kWh/year)	1,067,518
AC Primary Load (kWh/year)	663,975
Excess Electricity (kWh/year)	379,374 (35.5%)
Renewable Fraction (%)	93.1%
Unmet Electric Load (kWh/year)	59.1 (0.009%)
Capacity Shortage (kWh/year)	222 (0.03%)

Table 21: Energy Performance of Wind-PV-Diesel Generator (lithium-ion) System

According to the simulation results, the system produces 1,067,518kWh/year of electricity, of which 56% comes from the wind turbines and 39.7% from PVs. From the generated energy the system consumes 663,975kWh/year. An excess electricity of 35.5% is observed, which occurs from the energy production from wind turbines and photovoltaics when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is negligible at 0.009%. Additionally, 95.7% of the total generated electricity comes from the wind turbines and the PVs and only 4.28% from the diesel engine, and so the system acquires a very large renewable energy fraction at 93.1%.

Figure 39 presents the average monthly electricity generation and the percentages of its cover by the wind turbines, PVs and the diesel generator.

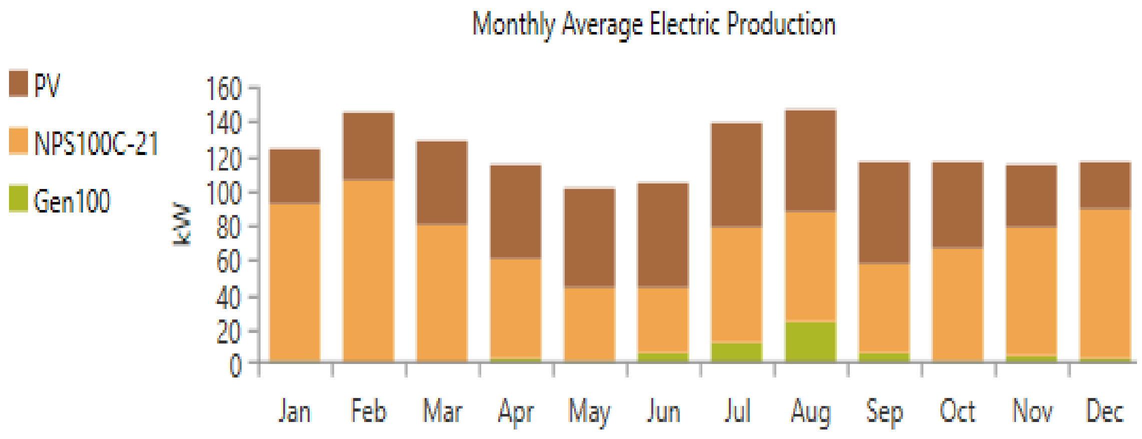

Figure 39: Monthly Average Electric Production from Wind-PV-Diesel (lithium-ion) System

From this figure, it is observed that the contribution of the generator to the electricity supply is minimized. It is mainly used in summer months (especially in August), because of the high energy demand due to tourists arrival. Furthermore, all the other months of the year the diesel's engine power supply is negligible due to the high wind speeds (especially in winter), which result to high generation of electricity from wind turbines. This reason also justifies the notable rate of excess electricity of the system which is 35.5% and considering that wind and solar energy rely on weather conditions the value of the excess electricity is normal. One noteworthy advantage of this system is that it acquires a very high renewable fraction due to the fact that the solar and wind power complement each other during the year. For instance, during winter the PVs power output is lower because of the lower percentages of solar radiation, while the power output of wind turbines is higher because of the high wind velocities during this period. On the other hand during summer months the wind velocities rates are decreasing and consequently the power output of the wind turbines, but due to the higher solar radiation of this time-period the power output of PVs is increasing.

Table 22 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation and replacement of the batteries and the installation of wind turbines and photovoltaics. It is also notable that, while the cost of installing the diesel generator is low, the cost of its fuel is extremely high comparing to its installation cost.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	354,134.59	0	38,771.23	0	0	392,905.82
Northern Power NPS100C-21 WT	390,000	0	53,372.29	0	0	443,372.29
Generic Generator	64,500	32,478.69	51,791.65	289,388.96	(26,258.50)	411,900.79
NEC DSS 170kWh 369kW	595,000	334,142.38	752.69	0	(183,785.75)	746,109.32
System Converter	46,294.01	25,997.97	0	0	(14,299.46)	57,992.51
System	1,449,928.60	392,619.04	144,687.85	289,388.96	(224,342.72)	2,052,280.73

Table 22: Cost Summary of Wind-PV-Diesel (lithium-ion) System

The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.226€, which is much lower than the current cost of electricity of Donousa (0.636€).

The reduced fuel consumption and operation of the diesel engine due to the high penetration of wind turbines, PVs and batteries in this system has led to a heavily decreased production of CO2 emissions, about 39,507kg/year, which is extremely lower than the 561,946kg/year of the initial system.

4.3.4 Wind-PV (lithium-ion) System

The diagram of the Wind-PV with lithium-ion battery system in HOMER is illustrated in Figure 40. After the optimization of HOMER the components of the most cost optimal combination of the Wind-PV (lithium ion) system are: 4 wind turbines of 100kW each, 524kW of PVs, a storage bank of 1,870kWh and a converter of 222kW.

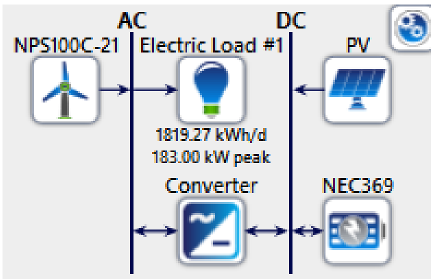

Figure 40: Wind-PV (lithium-ion) System

HOMER estimated that the total NPC of this system is *3,043.494€*, with a COE of *0.335€*. In addition, the diesel generator in this case consumes 15,104L of diesel per year. The energy performance of this system is presented in Table 23 below.

PVs electricity production (kWh/year)	785,135 (49.6%)
Wind turbines electricity production (kWh/year)	796,831 (50.4%)
Total electricity production (kWh/year)	1,581,966
AC Primary Load (kWh/year)	663,596
Excess Electricity (kWh/year)	893,586 (56.5%)
Renewable Fraction (%)	100%
Unmet Electric Load (kWh/year)	438 (0.06%)
Capacity Shortage (kWh/year)	646 (0.09%)

Table 23: Energy Performance of Wind-PV (lithium-ion) System

According to the simulation results, the system produces 1,581,966kWh/year of electricity, of which 50.4% comes from the wind turbines and 49.6% from PVs. From the generated energy the system consumes 663,596kWh/year. An excess electricity of 56.5% is observed, which occurs from the energy production from wind turbines and photovoltaics when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is negligible at 0.06%.

Figure 41 presents the average monthly electricity generation and the percentages of its cover by the wind turbines and PVs. From this figure, it is observed that the contribution of wind turbines in the electricity generation of the system is almost the same with the PVs. Moreover, the solar and wind power complement each other during the year. Specifically, during winter the PVs power output is lower because of the lower percentages of solar radiation, while the power output of wind turbines is higher because of the high wind velocities during this period. On the other hand, during a 7th month period (between April and October)the wind velocities rates are decreasing and consequently the power output of the wind turbines, but due to the higher solar radiation of this period the power output of PVs is increasing. The percentage of the excess electricity of this system is very high (56.5%), due to the fact that the system in order to cover constantly its load, relies only in renewable energy sources whose main characteristic is the unstable and unpredictable power generation and consequently batteries are unable to store all the excess electricity.

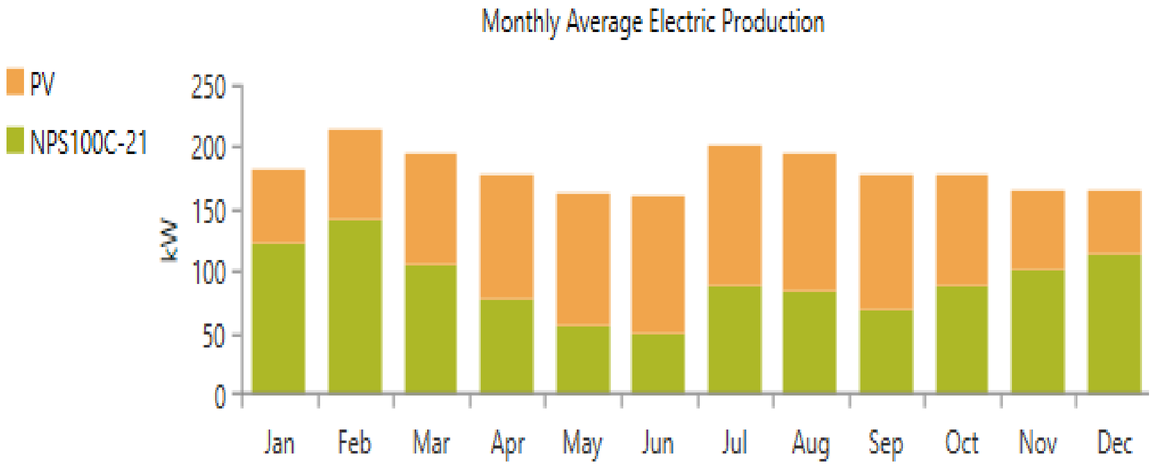

Figure 41: Monthly Average Electricity Production from Wind-PV (lithium-ion) System

Table 24 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation and replacement of the batteries (more than the sum of the costs of PVs and wind turbines) and this fact indicates the importance of storage in off-grid systems that rely only in renewable energy sources. Additionally, the NPC of this system is the highest than any other system that combine renewable and diesel power generation because of the implementation of more lithium-ion batteries, which require an expensive installation and replacement cost, in order to exploit effectively the unstable generation of the renewable power sources.

The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.335€, which is much lower than the current cost of electricity of Donousa (0.636€).

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	655,523.61	0	71,767.78	0	0	727,291.39
Northern Power NPS100C-21 WT	520,000	0	71,163.05	0	0	591,163.05
NEC DSS 170kWh 369kW	1,309,000	735,113.24	1,665.91	0	404,328.65	1,641,440.50
System Converter	66,735.07	37,477.33	0	0	20,613.37	83,599.03
System	2,551,258.68	772,590.57	144,586.74	0	424,942.02	3,043,493.97

Table 24: Cost Summary of Wind-PV (lithium-ion) System

A noteworthy advantage is that due to the exclusive use of renewable energy, this system produces zero pollutants.

4.3.5 Overall comparison of the different Hybrid Energy Systems with Lithium-Ion battery and results discussion

Table 25 below outlines the most important elements of the simulated systems in HOMER with lithium-ion batteries. The most cost-optimal solution is the combination of wind turbines with PVs and diesel generator (lowest NPC and COE). This is followed by the solution of wind turbines and diesel generator, which is slightly more advantageous than the combination of PV and diesel generator. The combination of PVs with wind turbines is the most expensive energy system. The constrained number of lithium-ion batteries alongside the limited use of the diesel generator, are the factors which determine that the combination with the wind turbines, PVs and diesel generator is the most cost-effective solution. At the same time, this use of the generator, during the summer months with the high demand, prevents the installation of extra renewable power generation.

Compared to the combination without the generator in the last most advantageous position, it is observed that the Wind-PV-Diesel Generator system has 241kW and 100kW (1 wind turbine) of less PVs and wind power installations, respectively and for this reason this system has a smaller rate of excess electricity per year. Additionally, the factor that justifies the high difference in cost between these 2 systems is the number of batteries and their high cost. Specifically, the Wind-PV System without the generator has 6 more lithium-ion batteries than the system with the diesel engine.

Hybrid Energy Systems	PV-Diesel Generator	Wind-Diesel Generator	Wind-PV-Diesel Generator	Wind-PV
Total NPC (€)	2,662,876	2,447,614	**2,052,281**	3,043,494
COE (€)	0.289	0.269	**0.226**	0.335
Total Electricity Production (kWh/year)	935,344	1,485,749	1,067.518	1,581,966
Excess Electricity (kWh/year)	**228,749 (24.5%)**	800,939 (53.9%)	379,374 (35.5%)	893,586 (56.5%)
Total Fuel (L/year)	27,301	29,930	15,104	**0**
CO_2 emissions (Kg/year)	71,408	76,717	39,507	**0**
Selection	X	X	V	X

Table 25: Summarized Characteristics of simulated Hybrid Energy Systems with Lithium-Ion battery

Continuing the results discussion about the Net Present Cost (NPC) and the cost of electricity per kWh (COE), it can be seen a cost difference between the other 2 combinations of PV-diesel and Wind-diesel generator. Despite the fact that, the diesel engine in the system with the wind turbines consumes 2,629 L/year more than the system with the PVs and its total cost is 39,899.83€ higher, the difference in the number of batteries determines the reason that the wind-diesel combination is cheaper. It has 3 batteries less and as a result its total battery cost is 447,665.59€ less than the PV-Diesel combination. However, the larger number of batteries offers some advantages to the PV-Diesel system and alongside the increased solar radiation of the island it ensures a reduced operation of the diesel generator that leads to 5,309 kg/year less CO2 emissions. Furthermore, the fact that this system has large storage capacity and do not depend on wind power resulted to a heavily decreased excess electricity by 572190 kWh/year than the wind-diesel system.

In general terms, it is observed an increased surplus of energy in combinations using wind turbines. The fluctuations of wind potential in the area create problems for the reliability of those systems and the necessary over-dimensioning of the wind generation in order to fully cover the load causes higher percentages of excess electricity. Moreover, the most environmentally friendly systems are those that obtain the highest percentage of renewable energy sources penetration. Diesel generators are the main sources of environmental pollutants in our systems. The quantity of emissions depends on the use of the generator (specifically its size, operating hours and fuel consumption) and this is the reason that Wind-PV-Diesel combination has reduced emissions.

4.4 Combinations of Hybrid Energy Systems with Vanadium-Flow Battery

4.4.1 PV-Diesel Generator (Vanadium-flow) Battery

The diagram of the PV-Diesel Generator with vanadium-flow battery system in HOMER is illustrated in Figure 42.

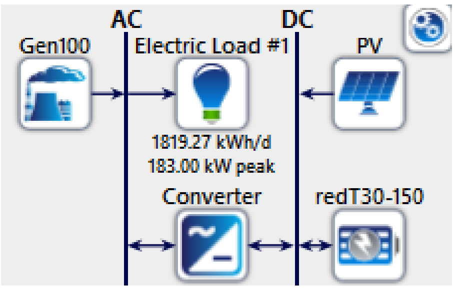

Figure 42: PV-Diesel Generator System with Vanadium Flow Battery

After the optimization of HOMER the components of the most cost optimal combination of the PV-Diesel Generator (vanadium flow) system are: 651kW of PVs, a diesel generator of 150kW, a storage bank of 1,650kWh and a converter of 177kW.

HOMER estimated that the total NPC of this system is *2,309.929€*, with a COE of *0.254€*. In addition, the diesel generator in this case consumes 20,815L of diesel per year. The energy performance of this system is presented in Table 26 below.

According to the simulation results, the system produces 1,037,583kWh/year of electricity, of which 93.9% comes from the photovoltaic array. From the generated energy the system consumes 664,034kWh/year. An excess electricity of 22.5% is observed, which occurs from the energy production from PVs when the load is covered and the batteries are fully charged. From the above table it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability. Additionally, the diesel engine produces only 6.07% of the total generated electricity, and so the system acquires a very large fraction of renewable energy at 90.5%.

PVs electricity production (kWh/year)	974,650 (93.9%)
Diesel Generator electricity production (kWh/year)	62,934 (6.07%)
Total electricity production (kWh/year)	1,037,583
AC Primary Load (kWh/year)	664,034
Excess Electricity (kWh/year)	233,210 (22.5%)
Renewable Fraction (%)	90.5%
Unmet Electric Load (kWh/year)	0
Capacity Shortage (kWh/year)	0

Table 26: Energy performance of PV-Diesel (vanadium flow) System

Figure 43 presents the average monthly electricity generation and the percentages of its cover by the PVs.

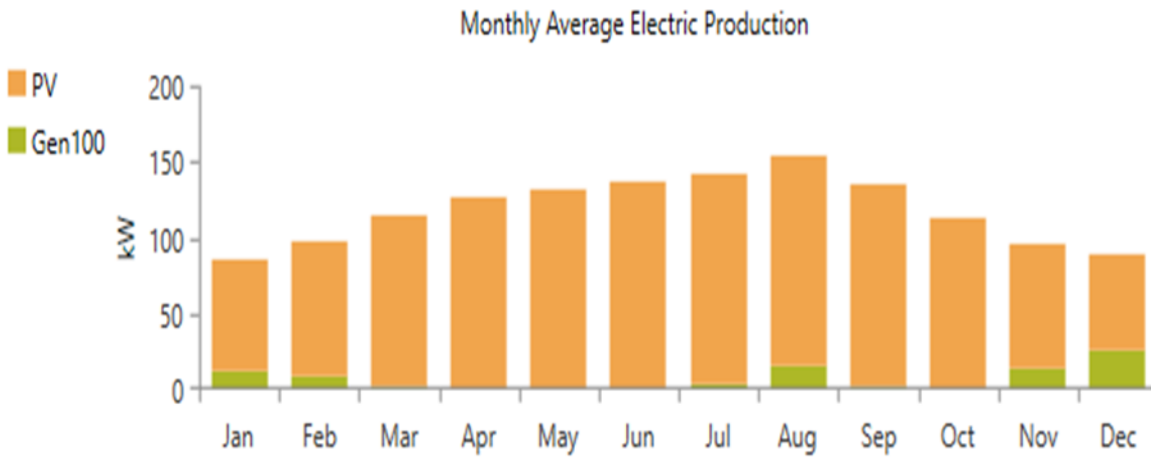

Figure 43: Monthly Average Electric Production from PVs-Diesel (vanadium-flow) System

From this figure, it is observed that the contribution of the generator to the electricity supply is minimized and thus, the high fraction of renewable energy occurs. The generator is mainly used in August, despite the high radiation values of the month, as the energy needs of the island are very high due to tourism. Furthermore, a notable use of the diesel engine can be seen from November to February, where there are the lowest rates of solar radiation during the year.

Table 27 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation of photovoltaic panels and for the installation and replacement of the batteries. It is also notable that while the cost of installing the diesel generator is low, the cost of its fuel is enormous (comparing to its installation cost), confirming that this is a major drawback of this power generation technology given the fact that the diesel engine has a low power supply.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	813,753.17	0	89,091.01	0	0	902,844.18
Generic Generator	64,500	39,306.55	71,744.67	398,804.10	(13,348.41)	561,006.92
redT 30kW-150kWh	660,000	0	180,644.66	0	(61,158.96)	779,485.71
System Converter	53,159.15	29,853.32	0	0	(16,419.99)	66,592.47
System	1,591,412.31	69,159.87	341,480.34	398,804.10	(90,927.35)	2,309,929.27

Table 27: Cost Summary of PV-Diesel (vanadium-flow) System

It is observed that, while the fraction of renewable energy is large (90.9%), the cost of the generator remains high despite the fact that it has a small share, since it is activated only when PV generation and batteries are insufficient to cover the load. This is because the diesel engine has high power output and consequently high fuel consumption. Furthermore, its limited lifetime (15,000 hours) requires its replacement during this 20 years period. Moreover, the average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.254€, which is much lower than the current cost of electricity of Donousa (0.636€).

The reduced fuel consumption and operation of the diesel engine due to the high penetration of PVs and batteries in this system has led to a heavily decreased production of CO_2 emissions, about 54,444kg/year, which is extremely lower than the 561,946kg/year of the initial system.

4.4.2 Wind-Diesel Generator (vanadium flow) System

The diagram of the Wind-Diesel Generator with vanadium-flow battery system in HOMER is illustrated in Figure 44.

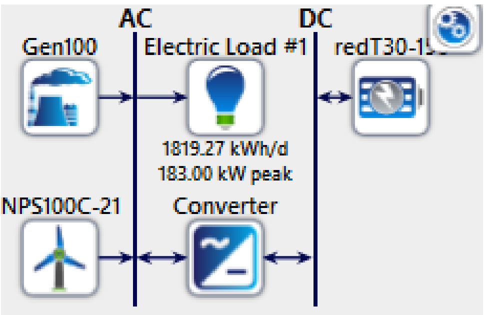

Figure 44: Wind-Diesel Generator with vanadium flow battery System

After the optimization of HOMER the components of the most cost optimal combination of the Wind-Diesel Generator (lithium ion) system are: 7 wind turbines of 100kW each, a diesel generator of 150kW, a storage bank of 1200kWh and a converter of 172kW.

HOMER estimated that the total NPC of this system is *2,272,884€*, with a COE of *0.250€*. In addition, the diesel generator in this case consumes 23,195L of diesel per year. The energy performance of this system is presented in Table 28.

Wind turbines electricity production (kWh/year)	1,394,454 (95.1%)
Diesel Generator electricity production (kWh/year)	72,323 (4.9%)
Total electricity production (kWh/year)	1,466,778
AC Primary Load (kWh/year)	663,868
Excess Electricity (kWh/year)	729,655 (49.7%)
Renewable Fraction (%)	89.1%
Unmet Electric Load (kWh/year)	166 (0.02%)
Capacity Shortage (kWh/year)	611 (0.09%)

Table 28: Energy Performance of Wind-Diesel (vanadium flow) System

According to the simulation results, the system produces 1,466,778kWh/year of electricity, of which 95.1% comes from the wind turbines. From the generated energy the system consumes 663,863kWh/year. An excess electricity of 49.7% is observed, which occurs from the energy production from wind turbines when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is extremely low at 0.02%. Additionally, the diesel engine produces only 4.94% of the total generated electricity, and so the system acquires a large fraction of renewable energy at 89.1%.

Figure 45 presents the average monthly electricity generation and the percentages of its cover by the wind turbines.

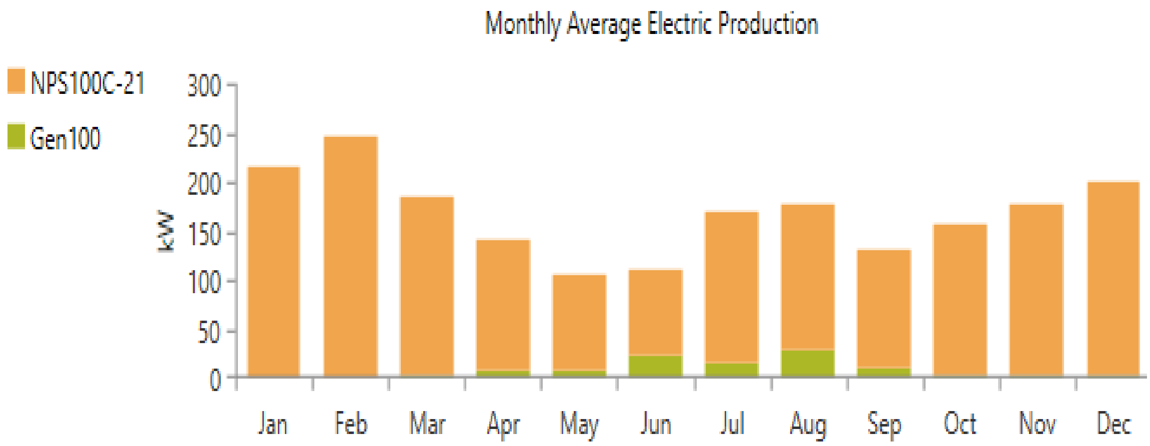

Figure 45: Monthly Average Electric Production of Wind-Diesel (vanadium flow) System

From this figure, it is observed that the contribution of the generator to the electricity supply is low and thus, the high fraction of renewable energy occurs. The generator is mainly used in summer months, because of the high energy demand due to tourists and the lower rates of average wind speeds in summer. Furthermore, from November until March the diesel engine power supply is negligible due to the high wind speeds, which result to high generation of electricity from wind turbines. This reason also justifies the high excess electricity of the system (49.7%), especially in winter months where the energy demand requirements are low and the electricity supply high due to the high wind potential of the region.

Table 29 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation of wind turbines. It is also notable that, while the cost of installing the diesel generator is low, the cost of its fuel is enormous (comparing to its installation cost), confirming that this is a major drawback of this power generation technology given the fact that it has a low power supply. Another disadvantage of this system is the high cost of the installation and replacement of the batteries, which are unable to exploit a significant amount of surplus electricity produced by the wind turbines.

It is observed that, while the fraction of renewable energy is large (89.1%), the cost of the generator remains high despite the fact that it has a small share, since it is activated only when wind generation and batteries are insufficient to cover the load. This is because the diesel engine has high power output and consequently high fuel consumption. Furthermore, its limited lifetime (15,000 hours) requires its replacement during this 20 years period.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Northern Power NPS100C-21 WT	910,000	0	124,535.34	0	0	1,034,535.34
Generic Generator	64,500	39,323.25	71,806.25	444,399.36	(13,308.56)	606,720.31
redT 30kW-150kWh	480,000	0	131,377.94	0	(44,479.24)	566,898.70
System Converter	51,672.19	29,018.26	0	0	(15,960.69)	64,729.76
System	1,506,172.19	68,341.52	327,719.53	444,399.36	(73,748.49)	2,272,884.10

Table 29: Cost Summary of Wind-Diesel (vanadium flow) System

The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.250€, which is much lower than the current cost of electricity of Donousa (0.636€).

The reduced fuel consumption and operation of the diesel engine due to the high penetration of wind turbines and batteries in this system has led to a heavily decreased production of CO2 emissions, about 60,668kg/year, which is extremely lower than the 561,946kg/year of the initial system.

4.4.3 Wind-PV-Diesel Generator (Vanadium Flow) System

The diagram of the Wind-PV-Diesel Generator with vanadium-flow battery system in HOMER is illustrated in Figure 46. After the optimization of HOMER the components of the most cost optimal combination of the Wind-PV-Diesel Generator (lithium ion) system are: 2 wind turbines of 100kW each, 390kW of PVs, a diesel generator of 150kW, a storage bank of 1200kWh and a converter of 145kW.

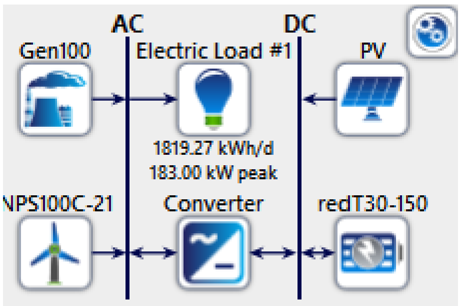

Figure 46: Wind-PV-Diesel Generator with vanadium flow battery System

HOMER estimated that the total NPC of this system is 1,818,960€, with a COE of 0.200€. In addition, the diesel generator in this case consumes 12,892L of diesel per year. The energy performance of this system is presented in Table 30 below.

PVs electricity production (kWh/year)	584,334 (57.2%)
Wind turbines electricity production (kWh/year)	398,416 (39%)
Diesel Generator electricity production (kWh/year)	38,109 (3.73%)
Total electricity production (kWh/year)	1,020,858
AC Primary Load (kWh/year)	664,030
Excess Electricity (kWh/year)	266,345 (26.1%)
Renewable Fraction (%)	94.3%
Unmet Electric Load (kWh/year)	3.71 (0.0006%)
Capacity Shortage (kWh/year)	42.5 (0.006%)

Table 30: Energy Performance of Wind-PV-Diesel (vanadium flow) System

According to the simulation results, the system produces 1,020,858kWh/year of electricity, of which 57.2% comes from PVs and 39% from wind turbines. From the generated energy the system consumes 664,030kWh/year. An excess electricity of 26.1% is observed, which occurs from the energy production from wind turbines and photovoltaics when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is negligible at 0.0006%. Additionally, 96.2% of the total generated electricity comes from the wind turbines and the PVs and only 3.73% from the diesel engine, and so the system acquires a very large renewable energy fraction at 94.3%.

Figure 47 presents the average monthly electricity generation and the percentages of its cover by the wind turbines, PVs and the diesel generator.

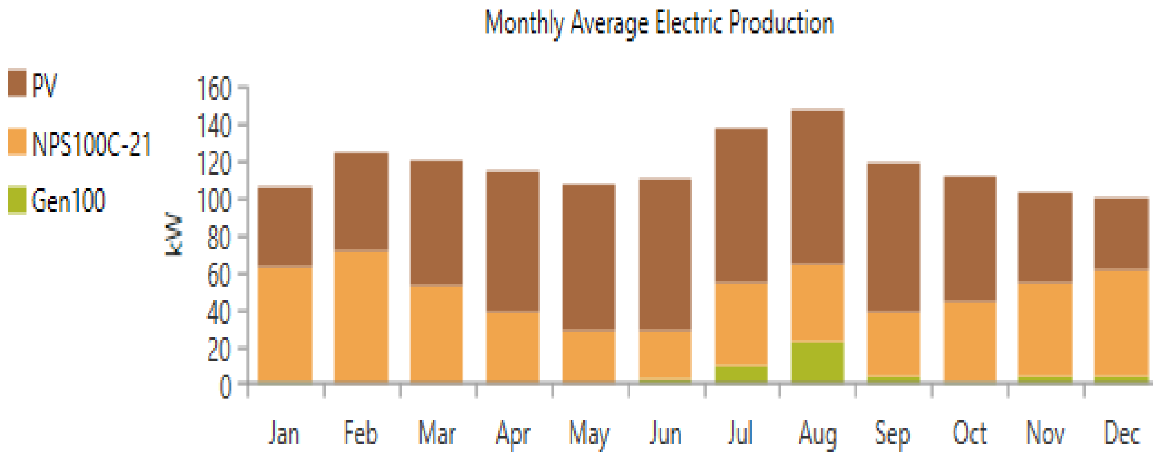

Figure 47: Monthly Average electric Production from Wind-PV-Diesel (vanadium flow) System

From this figure, it is observed that the contribution of the generator to the electricity supply is minimized. It is mainly used in summer months (especially in August), because of the high energy demand due to tourists arrival. Furthermore, all the other months of the year the diesel's engine power supply is negligible due to the high wind speeds (especially in winter), and the extended solar radiation which result to high generation of electricity. It is clear that solar power is the most exploitable energy source in this system and for this reason its excess electricity remains at relatively low levels (26.1%). One noteworthy advantage of this system is that it acquires a very high renewable fraction due to the fact that the solar and wind power complement each other during the year. For instance, during winter the PVs power output is lower because of the lower percentages of solar radiation, while the power output of wind turbines is higher because of the high wind velocities during this period. On the other hand during summer months the wind velocities rates are decreasing and consequently the power output of the wind turbines, but due to the higher solar radiation of this time-period the power output of PVs is increasing.

Table 31 illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation and maintenance of the batteries and the installation of photovoltaics. It is also notable that, while the cost of installing the diesel generator is low, the cost of its fuel is extremely high comparing to its installation cost.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	487,871.38	0	53,412.95	0	0	541,284.33
Northern Power NPS100C-21 WT	260,000	0	35,581.52	0	0	295,581.52
Generic Generator	64,500	30,605.96	47,665.56	247,007.73	(28,928.19)	360,851.06
redT 30kW-150kWh	480,000	0	131,377.94	0	(44,479.24)	566,898.70
System Converter	43,381.50	24,362.35	0	0	(13,399.83)	54,344.01
System	1,335,752.88	54,968.31	268,037.97	247,007.73	(86,807.26)	1,818,959.63

Table 31: Cost Summary of Wind-PV-Diesel (vanadium flow) System

The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.200€, which is much lower than the current cost of electricity of Donousa (0.636€).

4.4.4 Wind-PV (Vanadium Flow) System

The diagram of the Wind-PV with vanadium-flow battery system in HOMER is illustrated in Figure 48.

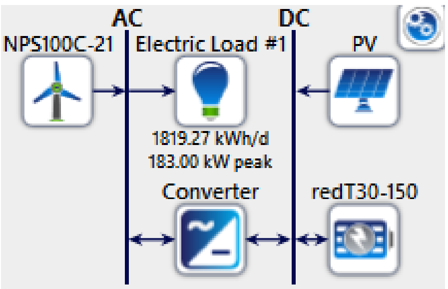

Figure 48: Wind-PV with Vanadium Flow battery System

After the optimization of HOMER the components of the most cost optimal combination of the Wind-PV-Diesel Generator (lithium ion) system are: 4 wind turbines of 100kW each, 545kW of PVs, a storage bank of 2250kWh and a converter of 205kW.

HOMER estimated that the total NPC of this system is *2,487,176€*, with a COE of *0.274€*. The energy performance of this system is presented in Table 32 below.

PVs electricity production (kWh/year)	816,293 (50.6%)
Wind turbines electricity production (kWh/year)	796,831 (49.4%)
Total electricity production (kWh/year)	1,613,124
AC Primary Load (kWh/year)	663,552
Excess Electricity (kWh/year)	868,900 (53.9%)
Renewable Fraction (%)	100%
Unmet Electric Load (kWh/year)	482 (0.07%)
Capacity Shortage (kWh/year)	662 (0.09%)

Table 32: Energy Performance of Wind-PV (vanadium flow) System

According to the simulation results, the system produces 1,613,124kWh/year of electricity, of which 49.4% comes from the wind turbines and 50.6% from PVs. From the generated energy the system consumes 663,552kWh/year. An excess electricity of 53.9% is observed, which occurs from the energy production from wind turbines and photovoltaics when the load is covered and the batteries are fully charged. From the above table, it can be seen that the system fully covers the energy needs of the load of Donousa with high reliability, since the energy deficit rate is negligible at 0.07%.

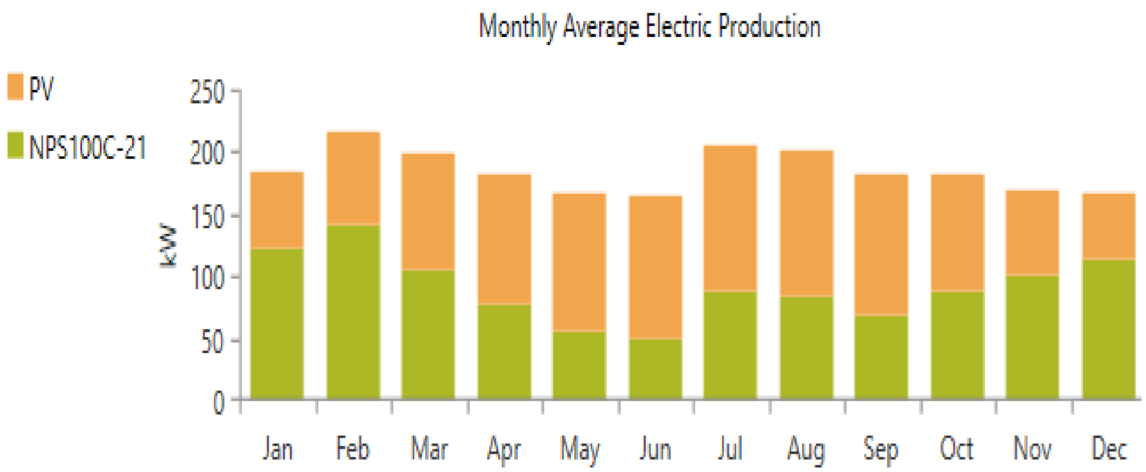

Figure 49: Monthly Average Electric Production of Wind-PV (vanadium flow) System

Figure 49 presents the average monthly electricity generation and the percentages of its cover by the wind turbines and PVs. It is observed that the contribution of wind turbines in the electricity generation of the system is almost the same with the PVs. Moreover, the solar and wind power complement each other during the year. Specifically, during winter the PVs power output is lower because of the lower percentages of solar radiation, while the power output of wind turbines is higher because of the high wind velocities during this period. On the other hand, during a 7th month period (between April and October)the wind velocities rates are decreasing and consequently the power output of the wind turbines, but due to the higher solar radiation of this period the power output of PVs is increasing. The percentage of the excess electricity of this system is very high (53.9%), due to the fact that the system in order to cover constantly its load, relies only in renewable energy sources whose main characteristic is the unstable and unpredictable power generation and consequently batteries are unable to store all the excess electricity.

COMPONENT	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Salvage (€)	Total(€)
Generic Flat Plate PV	681,538.46	0	74,615.93	0	0	756,154.39
Northern Power NPS100C-21 WT	520,000	0	71,163.05	0	0	591,163.05
redT 30kW-150kWh	900,000	0	246,333.63	0	(83,398.58)	1,062,935.06
System Converter	61,405.67	34,484.43	0	0	(18,967.21)	76,922.90
System	2,162,944.13	34,484.43	392,112.61	0	(102,365.78)	2,487,175.39

Table 33: Cost Summary of Wind-PV (vanadium flow) System

Table 33 above, illustrates the total cost of the system over the 20 years lifetime of the project. The cost for each part of the system is divided into the main economic characteristics of the Homer (Capital, Replacement, Operating, Fuel and Salvage). The highest price of system cost is for the installation and replacement of the batteries and this fact indicates the importance of storage in off-grid systems that rely only in renewable energy sources. Additionally, the NPC of this system is the relatively higher than the other systems that combine renewables and diesel power generation due to the fact that it utilizes more batteries in order to exploit effectively the unstable generation of the renewable power sources.

The average cost of electricity produced (COE) for the 20 years of lifetime of this project is 0.274€, which is much lower than the current cost of electricity of Donousa (0.636€).A noteworthy advantage is that due to the exclusive use of renewable energy, this system generates zero pollutants.

4.4.5 Overall comparison of the different Hybrid Energy Systems with Vanadium Flow battery and results discussion

Table 34 below outlines the most important elements of the simulated systems in HOMER with vanadium flow batteries.

Hybrid Energy Systems	PV-Diesel Generator	Wind-Diesel Generator	Wind-PV-Diesel Generator	Wind-PV
Total NPC (€)	2,309,929	2,272,884	**1,818,960**	2,487,176
COE (€)	0.254	0.250	**0.200**	0.274
Total Electricity Production (kWh/year)	1,037,583	1,466,778	1,020858	1,613,124
Excess Electricity (kWh/year)	**233,210 (22.5%)**	729,655 (49.7%)	266,345 (26.1%)	868,900 (53.9%)
Total Fuel (L/year)	20,815	23,195	12,892	**0**
CO_2 emissions (Kg/year)	54,444	60,668	33,721	**0**
Selection	X	X	V	X

Table 34: Summarized Characteristics of Simulated Hybrid Energy Systems with Vanadium Flow batteries in Homer

The most cost-optimal solution is the combination of wind turbines with PVs and diesel generator (lowest NPC and COE). This is followed by the solution of wind turbines and diesel generator, which is slightly more advantageous than the combination of PV and diesel generator. The combination of PVs with wind turbines is the energy system with the highest cost. The constrained number batteries alongside the limited use of the diesel generator are the factors which determine that the Wind-PV-Diesel combination is the most cost-effective solution. At the same time, this use of the generator, during the summer months with the high demand, prevents the installation of extra renewable power generation.

Compared to the combination without the generator in the last most advantageous position, it is observed that the Wind-PV-Diesel Generator system has 155kW and 200kW (2 wind turbines) of less PVs and wind power installations respectively and for this reason this system has a smaller rate of excess electricity per year. Additionally, this extra power generation alongside the larger number of batteries justifies the difference in cost between these 2 systems. Specifically, the Wind-PV System without the generator has 7 more vanadium-flow batteries than the system with the diesel engine.

Continuing the results discussion about the Net Present Cost (NPC) and the cost of electricity per kWh (COE), it can be seen a cost difference between the other 2 combinations of PV-diesel and Wind-diesel generator. Despite the fact that, the diesel engine in the system with the wind turbines consumes 2,380 L/year more than the system with the PVs and its total cost is 45713.39€ higher, the difference in the number of batteries determines the reason that the wind-diesel combination is cheaper. It has 3 batteries less and as a result its total battery cost is 212,587.01€ less than the PV-Diesel combination. However, the larger number of batteries offers some advantages to the PV-Diesel system and alongside the increased solar radiation of the island it ensures a reduced operation of the diesel generator that leads to 6,224 kg/year less $CO2$ emissions. Furthermore, the fact that this system has large storage capacity and do not depend on wind power resulted to a heavily decreased excess electricity by 496445 kWh/year than the wind-diesel system.

In general terms, it is observed an increased surplus of energy in combinations using wind turbines. The fluctuations of wind potential in the area create problems for the reliability of those systems and the necessary over-dimensioning of the wind generation in order to fully cover the load causes higher percentages of excess electricity. Moreover, the most environmentally friendly systems are those that obtain the highest percentage of renewable energy sources penetration. Diesel generators are the main sources of environmental pollutants in our systems. The quantity of emissions depends on the use of the generator (specifically its size, operating hours and fuel consumption) and this is the reason that Wind-PV-Diesel combination has reduced emissions.

4.5 Summary of the most cost-optimal solution

From the results analysis it is clear that for each type of battery the most economically-viable system combines wind turbines, photovoltaics and diesel generator.

Hybrid Energy Systems	Wind-PV-Diesel (Lead Acid)	Wind-PV-Diesel (Lithium Ion)	Wind-PV-Diesel (Vanadium Flow)
NPC (million €)	**1.63**	2.05	1.82
COE (€)	**0.180**	0.226	0.200
Total Battery Cost (€)	**533,444**	746,109	566,899
Total Electricity Production (MWh/year)	1,034	1,068	**1,021**
Excess Electricity (MWh/year)	320 (30.9%)	379 (35.5%)	**266 (26.1%)**
Renewable Fraction (%)	**96.5%**	93.1%	94.3%
CO_2 emissions (Kg/year)	**19,640**	39,507	33,721
Selection	V	X	X

Table 35: Comparison of the most cost optimal solutions for the different battery scenarios

The comparison of these results is presented in Table 35 above. It is revealed that the most cost-effective solution is the system of wind turbines, PVs and diesel generator with lead-acid batteries. Their low cost of installation overcame the higher energy efficiency and density of lithium-ion and vanadium flow batteries, respectively and led to a lower NPC and COE for this system and makes them a suitable type of storage for this small-scale application system.

Figure 50 below indicates the graphical representation of the NPC and the battery cost of the systems. It can be seen that the HES that utilizes the lithium ion battery has the highest NPC at 2.05 million € due to the higher cost of the lithium ion batteries compared to the other 2 types of batteries. Then, the system with the vanadium flow battery follows, which is decreased by 0.23 million € and finally the system with the lead acid battery, which is the most economic design for the island with an NPC of 1.63 million €. Moreover, another noteworthy element interpreted from this figure is the correlation between the NPC and the cost of storage and the effect of the latter in the total net present cost of the energy combination. Storage devices are essential in off-grid hybrid energy systems and thus their cost determines the NPC of these systems.

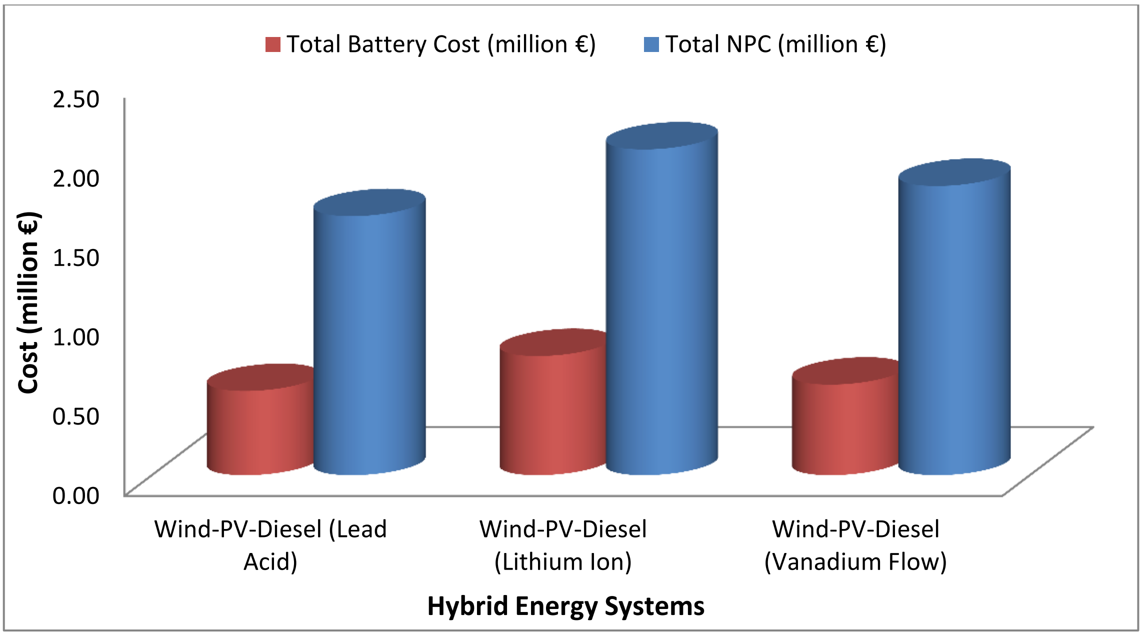

Figure 50: NPC and Battery Costs for the Optimized Energy Scenarios

Continuing the assessment of the results from a financial stand point, Figure 51 illustrates the COE of the energy scenarios. Similarly to the NPC of those systems the cost of electricity in the scenario with the lithium ion battery is the highest at 0.226€/kWh. Afterwards, the combination with the vanadium flow battery follows which is cheaper by 0.026€/kWh and eventually the system with the lead acid electrochemical devices which has the lowest COE at 0.18€/kWh.

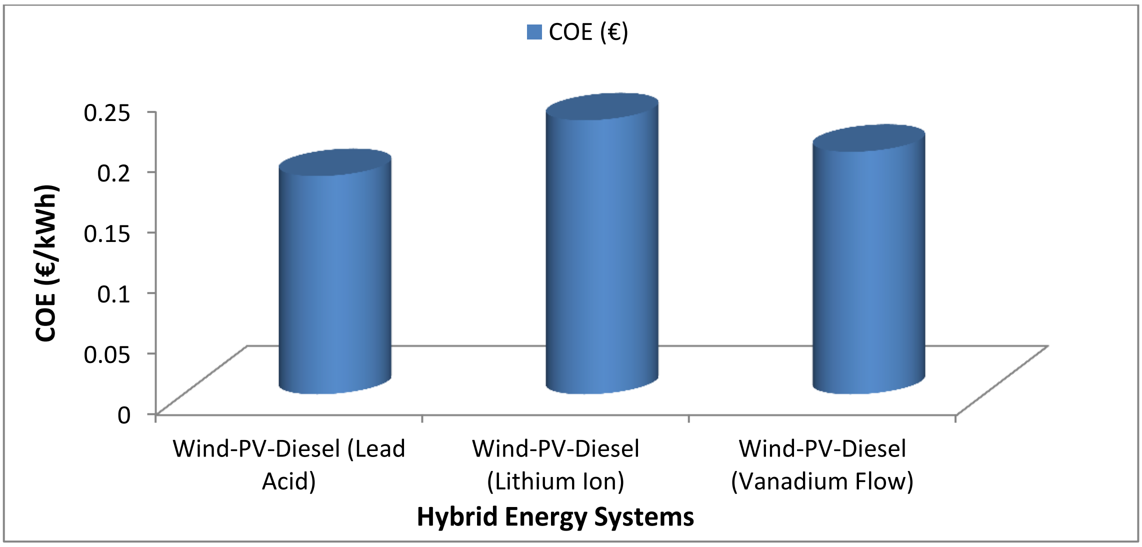

Figure 51: COE for the Optimized Energy Scenarios

The small capacity size of the lead acid batteries (7.15kWh per unit Nominal Capacity) alongside their low cost, allowed a higher renewable energy penetration in the system's electricity supply (96.5% R.F) and thus, it resulted to a reduced operation of the diesel engine, which is responsible for the production of various pollutants. Consequently, this system produces significantly less CO_2 emissions than the lithium-ion and vanadium-flow systems as presented in Figure 52 below. Specifically, the combination with the lithium ion batteries produces more than double CO_2 emissions than the lead acid system (39,507kg/year and 19,607kg/year respectively), while the combination of vanadium flow batteries has a high CO_2 production as well at 33,721kg/year. If the installation of extra renewable power generation and storage occurs in these 2 systems in order to decrease the operation of the generator, then the Carbon Dioxide emissions will be reduced but their NPC and COE will increase.

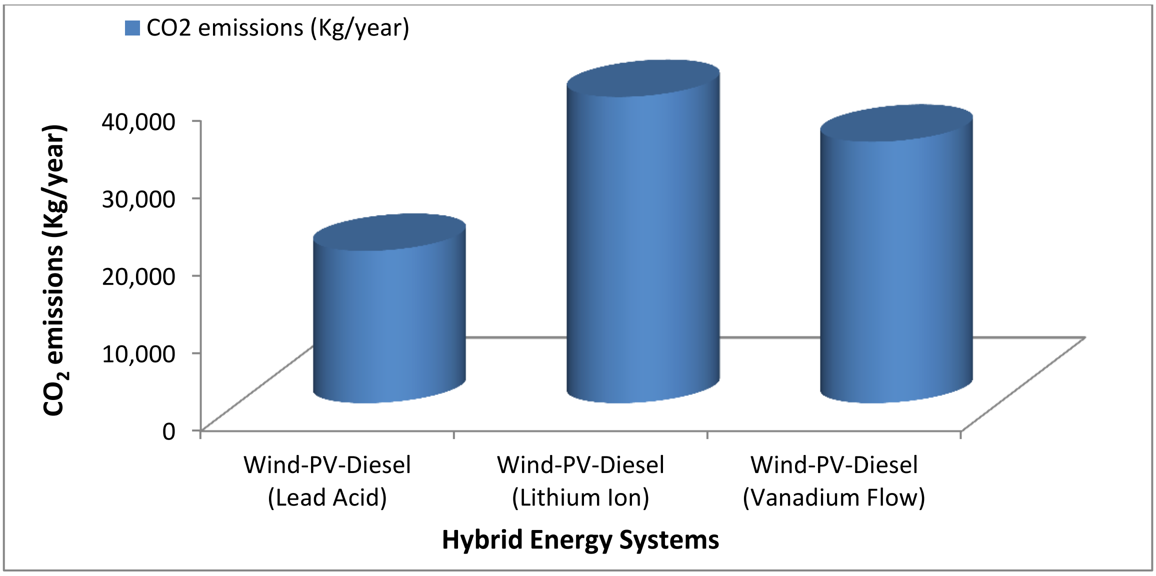

Figure 52: CO_2 Emissions for the Optimized Energy Scenarios

Finally, due to the fact that the combination with the Vanadium Flow batteries relies more on the photovoltaics electricity production (57.2%) than wind electricity production (39%), it acquires the advantage of a lower rate of excess electricity (26.1%) compared to the other 2 systems. Figure 53 below presents the total electricity production and the excess electricity of these scenarios. It is observed that higher electricity generation results to more excess electricity. Thus, after the vanadium flow combination, the lead acid combination follows which produces 13MWh/year more electricity and has a percentage of 4.8% of an extra electrical energy. Finally, the lithium ion system produces 1068MWh/year and acquires the largest proportion of excess electricity at 35.5%.

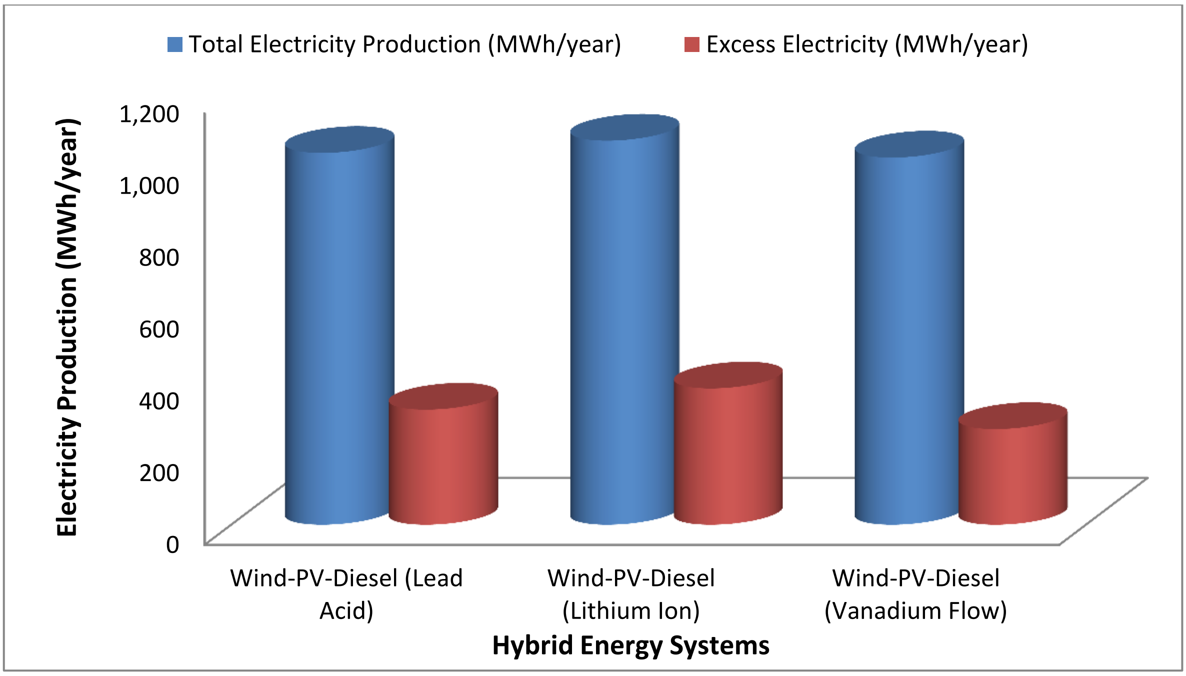

Figure 53: Electricity Production and Excess Electricity for the Optimized Energy Scenarios

4.6 Sensitivity Analysis of the Selected Energy System

From the results comparison, the most suitable energy solution for the island Donousa deemed to be the combination of wind turbines, PVs, diesel generator and lead acid batteries. Despite the fact that the diesel engine has a small contribution to the overall electricity generation of the hybrid energy system, its total cost is high due to the fuel imports and the price of the fuel. In addition, the cost of diesel in Greece appears a high level of uncertainty because it constantly changes as it is affected by various policies and legislations as well as the global oil fluctuations. Consequently, it was decided to implement a sensitivity analysis on the fuel price and examine the impact of its change to the NPC, COE, energy performance and emissions of the system.

Diesel Fuel Price (€/L)	PVs (kW)	Wind Turbines (kW)	Diesel Generator (kW)	Batteries (kWh)	Converter (kW)
1.00	250	300	150	2202	149
1.20	272	300	150	2302	153
1.40	276	300	150	2310	152
1.60	276	300	150	2445	156
1.80	281	300	150	2417	158

Table 36: Sensitivity Cases of the Selected Energy System

Table 36 above reveals the sensitivity cases of the diesel fuel price. It is observed that as the fuel price decreases, the capacity of PVs and the number of batteries are decreasing as well.

The energy performance of this system for the different prices of fuel is presented in Table 37 below. It is revealed that the fuel price reduction leads to the increase of electricity production from diesel generators and consequently the decrease of renewable energy fraction and excess electricity, as the electricity production from PVs is reducing. On the other hand, the increase of the fuel cost results to lower rates of diesel generator's electricity production and this fact has as a consequence the increase of electricity produced form PVs, which leads to higher percentages of renewable energy fraction and excess electricity. It is also notable to mention that the electricity production from PVs in the case with the 1.60€/L fuel price is slightly lower than the case with the 1.40€/L, despite the fact that the diesel engine produces less electricity. The reason for this is the increased number of batteries which also lead to a slightly lower excess electricity proportion.

Diesel Fuel Price (€/L)	PVs electricity production (kWh/year)	WT electricity production (kWh/year)	Diesel Generator electricity production (kWh/year)	Total electricity production (kWh/year)	Excess Electricity (kWh/year)	Renewable Fraction (%)
1.00	374,699 (37.3%)	597,623 (59.6%)	31,015 (3.09%)	1,033,337	289,264 (28.8%)	95.3%
1.20	407,158 (39.6%)	597.623 (58.1%)	24,268 (2.36%)	1,029,049	314,141 (30.5%)	96.3%
1.40	413,958 (40%)	597,623 (57.7%)	23,304 (2.25%)	1,034,885	319,898 (30.9%)	96.5%
1.60	412,834 (40%)	597,623 (57.9%)	21,819 (2.11%)	1,032,277	316,928 (30.7%)	96.7%
1.80	420,574 (40.5%)	597.623 (57.5%)	21,165 (2.04%)	1,039,363	324,016 (31.2%)	96.8%

Table 37: Energy Performance of the System for the different fuel prices

Regarding the financial parameters of the system for the various diesel prices which are illustrated in Table 38 below, it is clear that as the price of the fuel decreases the NPC and the COE are decreasing as well. Another significant fact that occurs from this sensitivity analysis is that the fuel consumption is strongly depends on the fuel price. By increasing its cost the total fuel consumption per year of the system is decreasing and this fact justifies also the lower electricity production of the diesel engine.

Diesel Fuel Price (€/L)	NPC (€)	COE (€)	Initial Capital Cost (€)	Operating Cost (€/year)	Total Fuel (L/year)	Fuel Cost (€/year)
1.00	1,588,447	0.175	1,182,019.53	29,698.33	10,035	10,035
1.20	1,613,594	0.178	1,226,987.51	28,249.94	7,820	9,384
1.40	1,634,874	0.180	1,233,681.46	29,315.80	7,509	10,512
1.60	1,655,356	0.182	1,256,724.36	29,128.63	7,007	11,211
1.80	1,674,008	0.184	1,258,913.68	30,331.65	6,795	12,232

Table 38: Characteristics of the System for the different fuel prices

In order to assess deeply the impact of the changes in fuel price of the energy system, it is necessary to investigate the changes in cost of its individual components. These alterations are given by Figure 54 below.

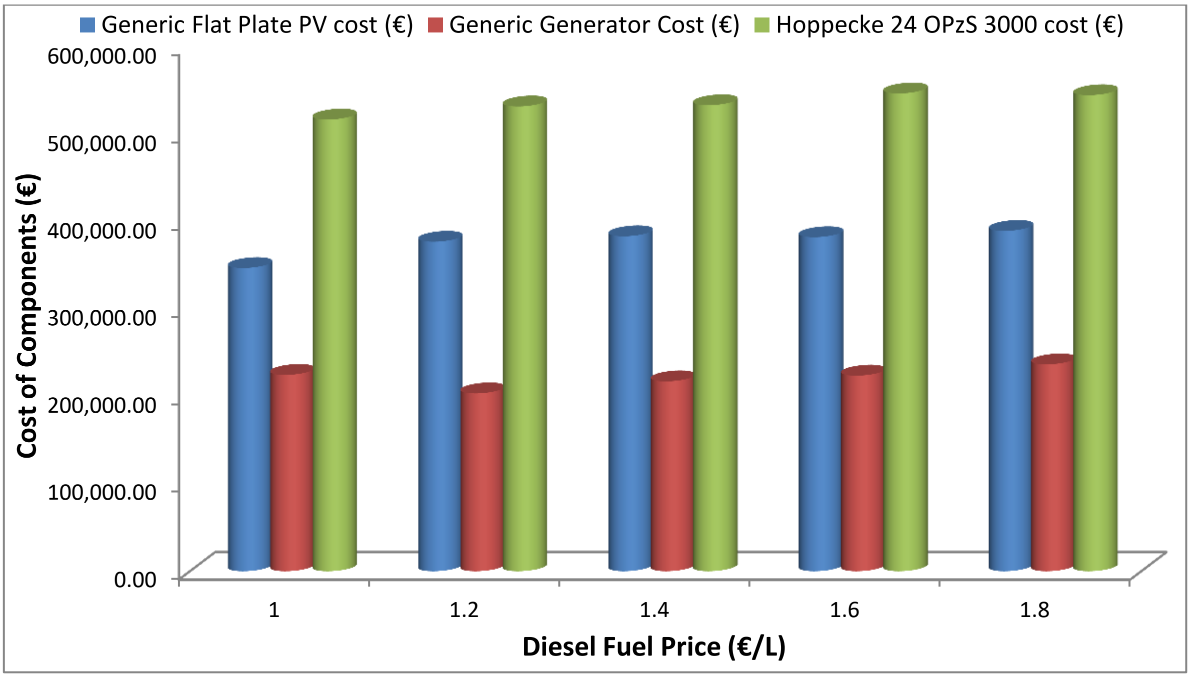

Figure 54: Cost of Components for the different Diesel Prices

It is observed that by increasing the price of the diesel the total cost of PVs and batteries and converters are increasing as well, while the price of the wind turbines remains stable. Furthermore, the cost of PVs in the system with fuel price set to 1.60€/L is slightly lower than the cost of PVs in the system with the fuel price set at 1.40€/L due to the fact that it utilizes more batteries. One other important information provided by this figure, is the change in the cost of the generator. As the fuel price decreases the cost of the generator decreases as well. However, when the fuel price is set at 1.00€/L, which is the lowest price of the fuel, the cost of the diesel engine is heavily increasing and becomes the 2nd most expensive diesel generator (after the generator of the system with the fuel price set at 1.8€/L). The reason for this is that in this case the operation of the diesel generator and its production of electricity is much higher comparing to the other cases. The electrical energy generated by the diesel engine in all the other cases ranges from 2.04% to 2.34%, while in this case it produces 3.09% electricity. The detailed costs of the components can be found in APENDIX 2.

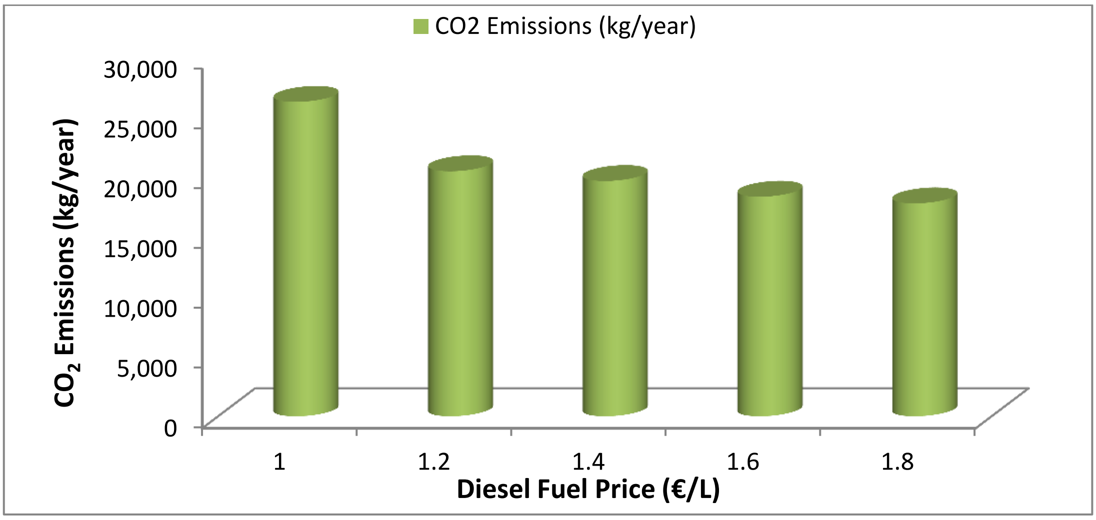

Figure 55: CO_2 Emissions for the different Fuel Prices

Figure 55 above, illustrates the CO_2 emissions according to the fuel price changes. It is observed that the carbon dioxide emissions are inversely proportional to the diesel fuel price. While the diesel price is increasing, the emissions are decreasing due to the fact that its operation is decreasing as well. A notable element of this graph is that the carbon dioxide production of the diesel generator for the system that has the lowest diesel price (1.0€/L) is significantly higher than the other systems, because its generator operates more than the generators in the other systems and consumes more fuel.

This sensitivity analysis demonstrated the impact of the diesel price fluctuations. These changes affect the system in terms of its cost, energy performance and emissions. The reduction of the fuel price is beneficial for the NPC and the COE of the system, but due to the increase of the percentage of electricity production from the generator the fuel consumption increases and consequently the CO_2 emissions. On the contrary, the rise of the cost of the diesel leads to the increase of the system's NPC and COE, as well as the renewable power generation and storage which result to higher excess electricity rates. However, the CO_2 emissions are decreasing because of the limited fuel consumption of the diesel engine.

5 FINAL REMARKS

5.1 Conclusions

In this paper the implementation of Hybrid Energy Systems has been investigated in an off-grid power system of a Greek island, which utilizes a diesel based power plant in order to produce electricity. From the literature review it is clear that the reduction of the dependence on fossil fuels has become a growing trend over the last years.

Moreover, one of the main drawbacks of the off-grid Greek islands is their reliance on fossil fuels. Despite the high wind and solar potential of the Aegean Sea region the exploitation rate of renewable energy sources is relatively low. Consequently, the combination of wind and solar power with an appropriate storage system and diesel generators can achieve a notable reduction in the cost of electricity, fuel imports and subsequently CO_2 emissions.

After the input of the electrical demand data of the island in HOMER, 4 different combinations of HESs were examined including a case of a pure renewable energy system. For these configurations 3 different types of battery were applied in order to assess which is the most suitable. After the output of the results the following conclusions were obtained:

- The most cost-effective solution is the system that combines wind turbines, photovoltaics, diesel generators and lead acid batteries. Its NPC and COE are 1.63 million€ and 0.180€, respectively.
- The replacement of an oil-based power unit with a HES, is an effective way of declining its fuel consumption and its pollutants.
- For every type of battery the most cost-optimal energy scenario is the Wind-PV-Diesel configuration. The lower storage capacity of this system alongside the limited operation of the diesel generator contributed to a decreased NPC and COE compared to the other scenarios.
- The operation of the diesel engine occurs only in periods of high demand or in periods where the renewable power generation and the batteries are unable to cover the load. Thus, its limited operation (especially in the Wind-PV-Diesel) system produces less emissions.

- The pure renewable energy system that utilizes lead acid batteries is the 2nd most cost effective solution (compared to the other lead-acid scenarios), because of their low price and the absence of the generator. On the contrary, the pure renewable energy scenarios that use Li-ion and vanadium flow batteries are the most expensive due to the high cost of those electrochemical devices.
- In general terms, the decreased cost of lead acid batteries overcame the higher energy efficiency and density of vanadium flow and lithium-ion batteries and rendered them as the most suitable storage option from an economic standpoint.
- The rate of excess electrical energy produced by a system is proportional to its wind power generation. The configurations with the higher percentages of excess electricity rely more on wind energy. Consequently, the systems with the lower wind penetration or without (PV-Diesel system), acquire also the lowest rates of excess electricity.
- Regarding the most economic systems of each type of batteries which is the PV-Wind-Diesel after the lead acid scenario, the vanadium flow system follows with 184,086€ and 14.081kg/year higher NPC and CO_2 production, respectively. Then, the 3rd scenario is the lithium-ion system, which produces 19,867kg/year more CO_2 emissions than the lead acid system and has an NPC increased by 417,407€.
- From an environmental point of view, the most preferred scenarios are the pure renewable energy systems, which produce zero pollutants. If the interconnection of the off-grid islands with the mainland is achieved, then economic benefits can potentially occur due to the fact that the excess electricity could be exported to the grid and increase the energy profits of the island.

After the sensitivity analysis associated with the fuel price of the most cost-optimal scenario, the following conclusions were made:

- Given the fact that the diesel engine contributes only 2.25% to the total electricity production of this system, the fluctuations of the diesel price have a significant influence in various parameters of this configuration.
- The diesel price is proportional to the NPC and COE of the system. Specifically, a steady increase of 0.20€ in fuel prices, causes a 1.1% to 1.6% increase in its NPC and a 0.002€/kWh increase in its COE. This is beneficial because the

operation and the production of emissions of the diesel engine are reducing and the installation of more renewable generation is favored.

- On the contrary, the diesel price is inversely related to the fuel consumption of the generator and the CO_2 emissions. The increase of fuel cost leads to the reduction of the operation of the diesel power unit and subsequently to the decrease of its total fuel consumption and pollutants.
- Finally, the decline of fuel consumption results to the increment of the renewable power generation and storage and for this reason the total NPC is increasing.

5.2 Limitations and Uncertainties of this study

Uncertainties are usually part of a project’s development. One noteworthy uncertainty of this study is associated with the cost of the components. The prices of them were estimated according to the current general costs of their specific technology and it was assumed that over the lifetime of this project these prices will remain stable.

After the result analysis, it was found that the most cost-effective scenario is the system that consists of PVs, wind turbines, diesel generator and lead-acid batteries. Afterwards, a sensitivity analysis was conducted in order to examine the impact of the diesel price fluctuations to the system. The cost of PVs and wind turbines were assumed that they will not change during the 20 years period of the project’s lifetime. Thus, a sensitivity analysis is needed in order to examine in detail the consequences of these changes in the system’s energy performance and economics. Additionally, another major factor that heavily affects all the parameters of this configuration is the battery and its cost. It was assumed that it will remain stable but in reality their prices are constantly changing in order to be more competitive in the market. For instance, estimations have shown that the price of Li-Ion batteries will mark a notable decrease over the next years (Gaines, 2018). Therefore, the system with the lithium-ion battery can potentially reduce its NPC and COE.

Some extra limitations and simplifications are summarized below:

- It was assumed that over the lifetime of this project the energy demand will remain the same. A change in the electric load of the island over this period, which is very likely to happen, can heavily affect the implemented energy systems.

- HOMER database has access to the weather data of the region where the island is located. However, a more precise data acquisition is required in order to assess more accurate the integration of renewable energy sources in the power system.
- The input load profile of the island in HOMER was the hourly demand of Donousa. In case of power fluctuations which can occur shorter period than this time-step, the reliability of the system is decreasing.
- In this paper it was decided to investigate 3 different types of electrochemical devices as a storage option. Additional storage systems such as pumped storage hydropower, compressed air energy storage (CAES) and hydrogen storage can be an effective solution.

5.3 Direction for future investigations

There are various future suggestions that can be addressed in the area of this project and they are indicated below:

- Investigation of additional storage options in order to examine their feasibility and their beneficial effects. Particularly, the hydrogen fuel cell technology, which is constantly developing and many scientists and researchers advocate their utilization in energy projects.
- Alternative types of fuel such as biodiesel and biogas should be examined. These types of fuel heavily decrease the emissions and considered environmental friendly.
- Multiple sensitivity analysis should be carried out in order to comprehend the impacts of the alternations in the costs of photovoltaics, wind turbines and batteries.
- A deeper study in the factors that affect the energy demand of Donousa such as the annual fluctuations in the rate of tourist arrival and the inhabitants of the island, as well as, their energy behaviour. Furthermore, the use of air-conditioning systems and large fish fridges, which consume a significant amount of electricity and affect the electric load should be studied.

- Development of desalination technology and investigation of its feasibility and how it can be combined with the proposed energy system of the island, in order to replace the tanker ships that transfer large amounts of drinking water from the mainland of Greece. Additionally, the water consumption of the island should be taken into consideration and subsequently its impact on the overall energy demand.
- Perform a detailed payback analysis of the proposed energy system and the current system of the island.

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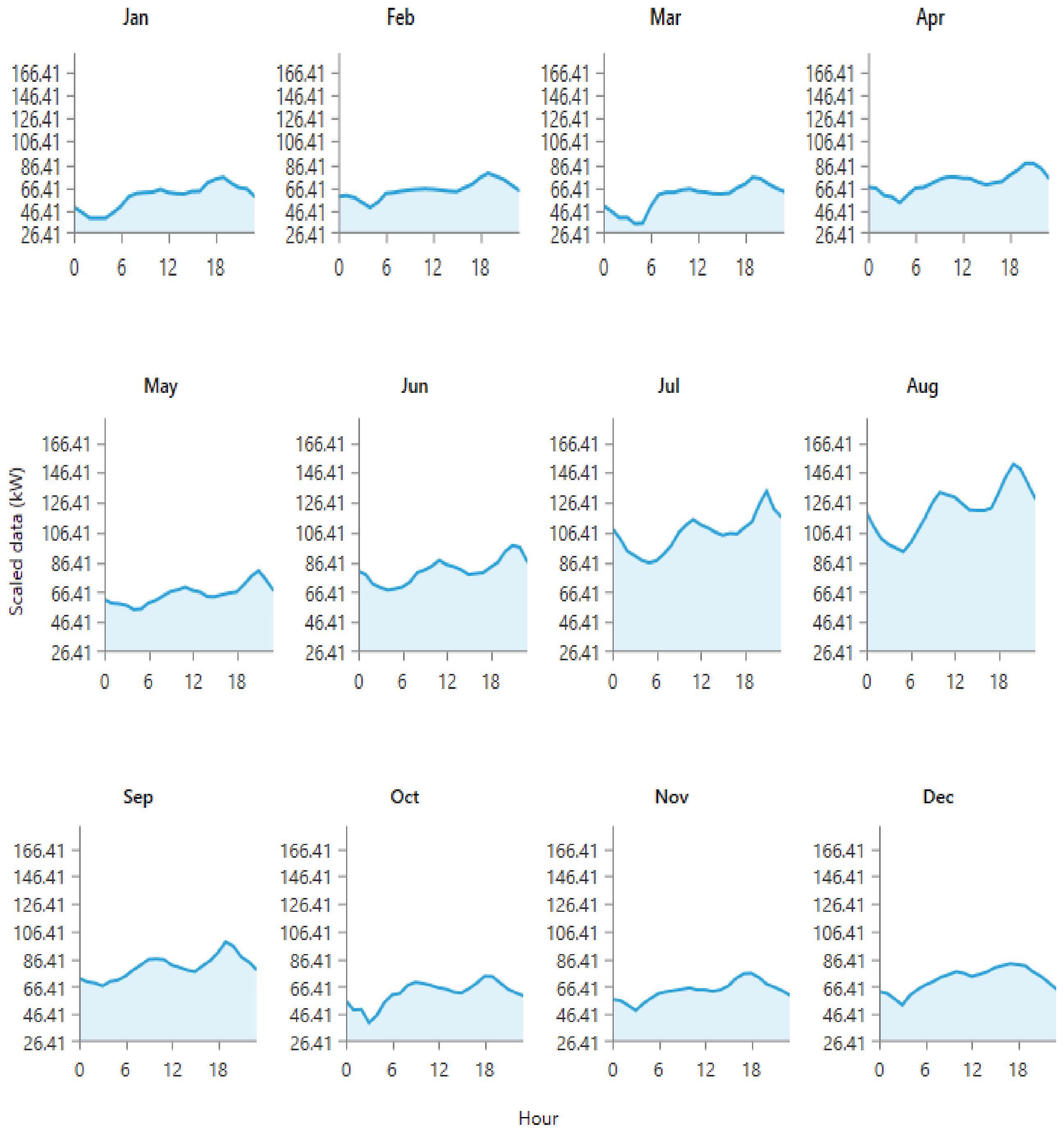
APENDIXES

APENDIX 1: Hourly Demand Profile of Donousa



APENDIX 2: Emissions of the Hybrid Energy Systems

Pollutants	PV-Diesel (lead acid) system (Kg/year)	WT-Diesel (lead acid) system (Kg/year)	Wind-PV-Diesel (lead acid) system (Kg/year)	Initial System Pollutants (Kg/year)
Carbon Dioxide	34,823	50,402	19,640	561,946
Carbon Monoxide	237	543	134	3,542
Unburned Hydrocarbons	9.59	13.9	5.41	155
Particulate Matter	0.948	1.37	0.535	21.5
Sulfur Dioxide	85.3	124	48.1	1,376
Nitrogen Oxides	19.0	27.4	10.7	3,328

Pollutants	PV-Diesel (lithium-ion) system (Kg/year)	Wind-Diesel (lithium-ion) system (Kg/year)	Wind-PV-Diesel (lithium-ion) system (Kg/year)	Initial System Pollutants (Kg/year)
Carbon Dioxide	71,408	76,717	39,507	561,946
Carbon Monoxide	486	522	269	3,542
Unburned Hydrocarbons	19.7	21.1	10.9	155
Particulate Matter	1.94	2.09	1.08	21.5
Sulfur Dioxide	175	188	96.8	1,376
Nitrogen Oxides	38.9	41.8	21.5	3,328

Pollutants	PV-Diesel (vanadium flow) system (Kg/year)	Wind-Diesel (vanadium flow) system (Kg/year)	Wind-PV-Diesel (vanadium flow) System (Kg/year)	Initial System Pollutants (Kg/year)
Carbon Dioxide	54,444	60,668	33,721	561,946
Carbon Monoxide	370	413	229	3,542
Unburned Hydrocarbons	15	16.7	9.28	155
Particulate Matter	1.48	1.65	0.918	21.5
Sulfur Dioxide	133	149	82.6	1,376
Nitrogen Oxides	29.6	33	18.4	3,328

APENDIX 3: Total Cost of Components of the WIND-PV-DIESEL System with Lead Acid Battery for the different fuel prices

Diesel Fuel Price (€/L)	1.00	1.20	1.40	1.60	1.80
Generic Flat Plate PV cost (€)	347,093.34	377,160.92	383,460.18	382,419.41	389,589.37
Northern Power NPS100C-21 WT cost (€)	443,372.29	443,372.29	443,372.29	443,372.29	443,372.29
Generic Generator Cost (€)	224,791.05	203,604.69	217,427.58	223,951.76	236,798.84
Hoppecke 24 OPzS 3000 cost (€)	517,108.74	532,054.26	533,443.29	546,986.47	544,957.28
System Converter cost (€)	56,081.79	57,401.41	57,170.02	58,625.42	59,290.65
System (NPC) (€)	1,588,447.21	1,613,593.56	1,634,874.06	1,655,355.55	1,674,008.42

APENDIX 4: Annual Economics of Configurations with Lead-Acid Batteries

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€56,820.95	€0.00	€6,220.85	€0.00	€0.00	€63,041.80
Generic Medium Genset (size-your-own)	€4,713.12	€0.00	€3,339.00	€18,639.15	(€23.29)	€26,667.98
Hoppecke 24 OPzS 3000	€38,262.94	€22,936.62	€5,232.00	€0.00	(€4,469.24)	€61,962.31
System Converter	€3,959.72	€2,223.71	€0.00	€0.00	(€1,223.09)	€4,960.34
System	€103,756.73	€25,160.33	€14,791.85	€18,639.15	(€5,715.63)	€156,632.43

PV-Diesel Generator System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic Medium Genset (size-your-own)	€4,713.12	€2,513.85	€4,131.00	€26,977.82	(€1,694.56)	€36,641.23
Hoppecke 24 OPzS 3000	€31,417.73	€14,707.71	€4,296.00	€0.00	(€12,087.01)	€38,334.43
Northern Power NPS100C-21	€56,995.87	€0.00	€7,800.00	€0.00	€0.00	€64,795.87
System Converter	€4,141.59	€2,325.85	€0.00	€0.00	(€1,279.27)	€5,188.16
System	€97,268.31	€19,547.41	€16,227.00	€26,977.82	(€15,060.83)	€144,959.70

Wind-Diesel Generator System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€25,255.09	€0.00	€2,764.97	€0.00	€0.00	€28,020.06
Generic Medium Genset (size-your-own)	€4,713.12	€0.00	€1,728.00	€10,512.32	(€1,065.65)	€15,887.79
Hoppecke 24 OPzS 3000	€28,346.17	€14,905.37	€3,876.00	€0.00	(€8,147.91)	€38,979.62
Northern Power NPS100C-21	€28,497.94	€0.00	€3,900.00	€0.00	€0.00	€32,397.94
System Converter	€3,334.80	€1,872.77	€0.00	€0.00	(€1,030.07)	€4,177.51
System	€90,147.12	€16,778.14	€12,268.97	€10,512.32	(€10,243.63)	€119,462.91

PV-Wind-Diesel Generator System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€47,763.42	€0.00	€5,229.22	€0.00	€0.00	€52,992.64
Hoppecke 24 OPzS 3000	€43,352.96	€20,283.97	€5,928.00	€0.00	(€16,695.10)	€52,869.83
Northern Power NPS100C-21	€28,497.94	€0.00	€3,900.00	€0.00	€0.00	€32,397.94
System Converter	€4,375.15	€2,457.02	€0.00	€0.00	(€1,351.41)	€5,480.75
System	€123,989.47	€22,740.99	€15,057.22	€0.00	(€18,046.52)	€143,741.16

PV-Wind System

APENDIX 5: Annual Economics of Configurations with Lithium-Ion Batteries

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€51,974.74	€0.00	€5,690.28	€0.00	€0.00	€57,665.02
Generic Medium Genset (size-your-own)	€4,713.12	€3,187.28	€6,637.50	€38,221.34	(€72.79)	€52,686.45
NEC DSS 170kWh 369kW	€60,868.67	€34,182.86	€77.00	€0.00	(€18,801.33)	€76,327.19
System Converter	€3,974.71	€2,232.13	€0.00	€0.00	(€1,227.72)	€4,979.12
System	€121,531.24	€39,602.27	€12,404.78	€38,221.34	(€20,101.85)	€191,657.78

PV-Diesel Generator System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic Medium Genset (size-your-own)	€4,713.12	€3,194.85	€6,678.00	€41,062.61	(€46.59)	€55,601.99
NEC DSS 170kWh 369kW	€34,782.10	€19,533.06	€44.00	€0.00	(€10,743.62)	€43,615.54
Northern Power NPS100C-21	€66,495.18	€0.00	€9,100.00	€0.00	€0.00	€75,595.18
System Converter	€3,223.75	€1,810.40	€0.00	€0.00	(€995.76)	€4,038.39
System	€109,214.15	€24,538.32	€15,822.00	€41,062.61	(€11,785.97)	€178,851.10

Wind-Diesel Generator System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€25,877.19	€0.00	€2,833.08	€0.00	€0.00	€28,710.27
Generic Medium Genset (size-your-own)	€4,713.12	€2,373.27	€3,784.50	€21,146.12	(€1,918.75)	€30,098.26
NEC DSS 170kWh 369kW	€43,477.62	€24,416.33	€55.00	€0.00	(€13,429.52)	€54,519.42
Northern Power NPS100C-21	€28,497.94	€0.00	€3,900.00	€0.00	€0.00	€32,397.94
System Converter	€3,382.78	€1,899.71	€0.00	€0.00	(€1,044.88)	€4,237.61
System	€105,948.65	€28,689.31	€10,572.58	€21,146.12	(€16,393.16)	€149,963.50

PV-Wind-Diesel Generator System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€47,900.18	€0.00	€5,244.19	€0.00	€0.00	€53,144.37
NEC DSS 170kWh 369kW	€95,650.76	€53,715.92	€121.00	€0.00	(€29,544.95)	€119,942.73
Northern Power NPS100C-21	€37,997.25	€0.00	€5,200.00	€0.00	€0.00	€43,197.25
System Converter	€4,876.44	€2,738.53	€0.00	€0.00	(€1,506.25)	€6,108.72
System	€186,424.63	€56,454.45	€10,565.19	€0.00	(€31,051.21)	€222,393.07

PV-Wind System

APENDIX 6: Annual Economics of Configurations with Vanadium Flow Batteries

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€59,462.27	€0.00	€6,510.03	€0.00	€0.00	€65,972.30
Generic Medium Genset (size-your-own)	€4,713.12	€2,872.19	€5,242.50	€29,141.27	(€975.39)	€40,993.69
redT 30kW-150kWh Energy Storage	€48,227.28	€0.00	€13,200.00	€0.00	(€4,468.98)	€56,958.29
System Converter	€3,884.43	€2,181.43	€0.00	€0.00	(€1,199.84)	€4,866.02
System	€116,287.09	€5,053.62	€24,952.53	€29,141.27	(€6,644.21)	€168,790.30

PV-Diesel System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic Medium Genset (size-your-own)	€4,713.12	€2,873.41	€5,247.00	€32,472.99	(€972.48)	€44,334.04
Northern Power NPS100C-21	€66,495.18	€0.00	€9,100.00	€0.00	€0.00	€75,595.18
redT 30kW-150kWh Energy Storage	€35,074.38	€0.00	€9,600.00	€0.00	(€3,250.17)	€41,424.21
System Converter	€3,775.77	€2,120.41	€0.00	€0.00	(€1,166.27)	€4,729.91
System	€110,058.46	€4,993.83	€23,947.00	€32,472.99	(€5,388.92)	€166,083.35

Wind-Diesel System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€35,649.56	€0.00	€3,902.97	€0.00	€0.00	€39,552.53
Generic Medium Genset (size-your-own)	€4,713.12	€2,236.43	€3,483.00	€18,049.26	(€2,113.83)	€26,367.98
Northern Power NPS100C-21	€18,998.62	€0.00	€2,600.00	€0.00	€0.00	€21,598.62
redT 30kW-150kWh Energy Storage	€35,074.38	€0.00	€9,600.00	€0.00	(€3,250.17)	€41,424.21
System Converter	€3,169.96	€1,780.20	€0.00	€0.00	(€979.15)	€3,971.01
System	€97,605.64	€4,016.62	€19,585.97	€18,049.26	(€6,343.15)	€132,914.34

PV-Wind-Diesel Generator System

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Generic flat plate PV	€49,801.13	€0.00	€5,452.31	€0.00	€0.00	€55,253.43
Northern Power NPS100C-21	€37,997.25	€0.00	€5,200.00	€0.00	€0.00	€43,197.25
redT 30kW-150kWh Energy Storage	€65,764.47	€0.00	€18,000.00	€0.00	(€6,094.07)	€77,670.40
System Converter	€4,487.01	€2,519.83	€0.00	€0.00	(€1,385.96)	€5,620.88
System	€158,049.85	€2,519.83	€28,652.31	€0.00	(€7,480.03)	€181,741.96

PV-Wind System