Department of Electrical and Computer Engineering

Techno-economic analysis of an off-grid hybrid system in Donoussa island, Greece

A Thesis presented by

Katsivelakis Michail

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in

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The committee members, hereby, certify that have read the thesis presented by Katsivelakis Michail and that it is fully adequate in scope and quality as a partial requirement for the degree of Master of Science in Smart Grid Energy Systems.

Dr. Bargiotas Dimitrios
University of Thessaly
Principal Advisor

Dr. Tsoukalas Eleftherios
University of Thessaly
Committee Member

Dr. Daskalopulu Aspassia
University of Thessaly
Committee Member

Volos, Thessaly, April, 2020

Declaration of Authorship

I, Katsivelakis Michail, declare that this thesis titled, ”Techno-economic analysis of an off-grid hybrid system in Donoussa island, Greece” and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
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- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Katsivelakis Michail
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by

Katsivelakis Michail

Abstract

Hybrid Renewable Energy Systems is an attractive solution for the supply of electricity in remote areas like islands and communities where grid extension is difficult. Hybrid renewable energy system aim in the electrification of various areas and communities in a reliable, sustainable and environmental friendly way. Hybrid systems combine renewable energy sources with conventional units and battery storage in order to cater energy in an off-grid or on-grid system. The small isolated power systems cover their load demands by autonomous power stations which mainly use diesel generators and conventional units. In this thesis a hybrid renewable energy system is examined in three scenarios with different percentages of adoption rate (20%, 50% and 100%) for Donoussa island, Greece and a techno-economic analysis was studied. Primary load demand of 3460.3 day, peak load of 450 kW were involved during optimization of the hybrid system. The first scenario include system configuration with five conventional power units of the existing power system in combination with renewable energy sources (Wind Turbines and PV panels). The second scenario consists of three conventional units of the existing power system, renewable energy sources (Wind Turbines and PV panels) and battery energy storage. The third scenario is a 100% renewable scenario and include only renewables (Wind turbines and PV panels) and battery energy storage. HOMER software was used for detailed simulation and financial analysis and the optimal system configuration between the feasible configurations of each scenario was selected in respect to the minimum Excess Electricity percentage, lowest NPC (Net Present Cost) and LCoE (Levelized Cost of Energy). Moreover, for the first scenario the Excess Electricity, NPC and LCoE was 6.68%, 4.95 Millions € and 0.295 € respectively. For second scenario NPC and LCoE were found at 4.03 Millions € and 0.240 €, with a zero percentage in Excess Electricity. As for the third scenario two different cases were examined with a different amount of batteries. Excess Electricity was 41.8 % and 46.8 % for the two cases with a NPC and LCoE of 3.76 Millions € and 0.224 € and 5.22 Millions € and 0.311 €. Besides, sensitivity analysis was performed in optimal configuration of each scenario in order to be examined the behaviour of the selected system in changes in diesel price, average wind speed and average solar irradiation. Finally the purpose of this study is to examine the techno-economical feasibility and viability of a hybrid system in Donoussa island in different scenarios.

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Abbreviations

AC Alternative Current.

APS Autonomous Power Stations.

CC Capital Cost.

DC Direct Current.

DOD Depth of Discharge.

EU European Union.

GHG Greenhouse Gases.

GHI Global horizontal irradiation.

HEDNO Hellenic Electricity Distribution Network Operator S.A..

HRES Hybrid Renewable Energy System.

IEA International Energy Agency.

LCoE Levelized Cost of Energy.

NIIs Non-interconnected islands.

NPC Net Present Cost.

NREL National Renewable Energy Laboratory.

O & M Operational and Maintenance cost.

RES Renewable Energy Sources.

TPES Total Primary Energy Supply.

Chapter 1

Introduction

1.1 Background

Electricity power is vital for people's daily life and production, social and economic development. The power systems is composed of four parts: power generation, power transmission, voltage transformation, and power consumption. In some remote areas like villages, farms and islands is difficult a transmission and transformation system for a small demand of electricity to be constructed. As a result of this, there are people all over the world who have no access in electricity. According to IEA (International Energy Agency) a percentage of almost 13.2% of the global population did not have access to electricity in 2017 the number of people without electricity access fell below 1 billion, a fall of 97 million compared to 2016. [1]

Greece is a Mediterranean country located in south-eastern Europe with a population of 10.7 million approximately. An impressive increase in the share of renewables has occurred in Greece the last years. In Figure 1.1 can be seen the Renewable electricity generation by source (non-combustible) in Greece from 1990 to 2018. In general Greece is a country with great potential to RES (Renewable Energy Sources), especially solar and wind power. In recent years there is a growth in the share in wind and solar photovoltaics. According to IEA (International Energy Agency) the share of renewables in total primary energy supply (TPES) reached a peak in 2016 of 12.5% in Greece. Among IEA members Greece is in the 15th position in share of renewables in TPES (Figure 1.2). In addition, 31% of total electricity generation was produced from RES (Renewable Energy Sources) in 2016. In Figure 1.3 can be seen the Renewable energy share of electricity generation, from 1973 to 2016 in Greece. Furthermore, Greece has some targets including emissions reduction targets (a reduction of GHG emissions by 20% from the 1990 level by 2020), targets for the share of renewable energy (a renewable energy share of 20% in the gross final energy consumption beyond the 18% EU target by 2020) and energy efficiency targets (an energy efficiency target of 24.7 million tonnes of oil equivalent (Mtoe) in primary energy consumption or 18.4 Mtoe of final energy consumption by 2020). [1]

Greece has a unique characteristic of having about 6,000 islands, of which only 227 are inhabited. The islands of Greece have great potential of renewable energy sources especially for wind and solar energy. However only a percentage of almost 10% of the total installed renewable capacity is included on NIIs. The power systems of the non-interconnected islands

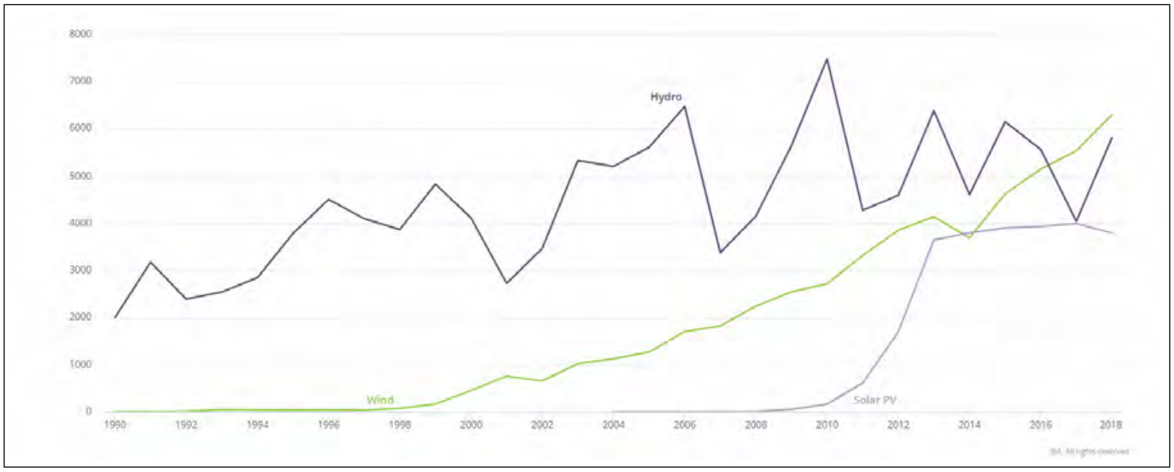

Figure 1.1: Renewable electricity generation by source (non-combustible), Greece 1990-2018. [iea]

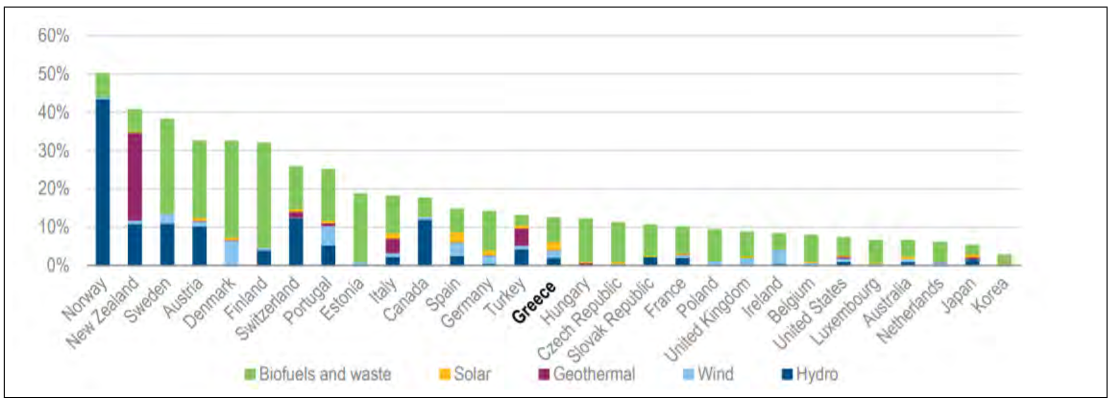

Figure 1.2: Renewable energy as a share of TPES in IEA member countries, 2016, IEA (2017a), World Energy Balances 2017

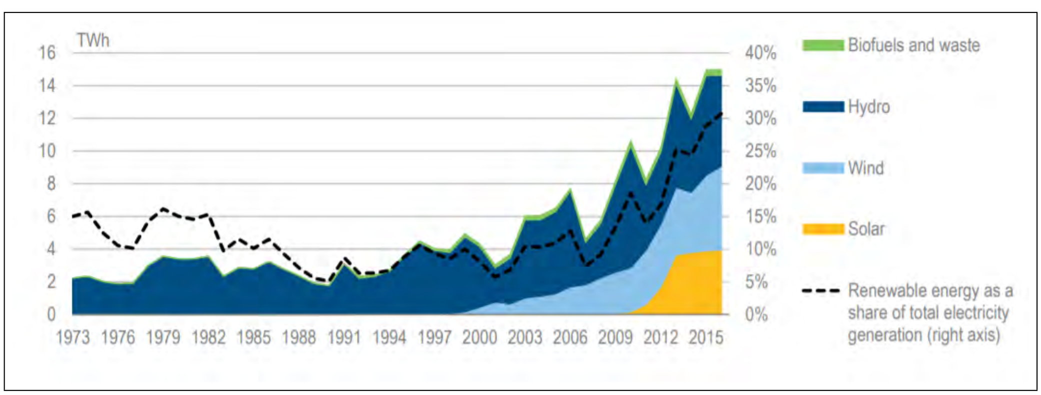

Figure 1.3: Renewable energy share of electricity generation, 1973-2016 IEA. [1]

(NIIs) are small. NIIs are not able to benefit from the cost advantage of large-scale generation capacity and are in a great extend dependent on on Autonomous Power Stations (APS) which are equiped with diesel generators and consume diesel or heavy oil (mazut). These APS are expensive due to the fuel price and are not environmental friendly as conventional units release large amounts of pollutants. Average variable electrical energy production cost as well as average total energy production cost are extremely high for NIIs in Greece. The weighted average of the variable cost all the NII electrical systems was rated at 130.519 €/MWh, between 2014 and 2017. [5] The issue of the interconnection of autonomous Greek islands with the mainland grid is a high priority issue for government's energy policy which is an expensive project.

The feasible solution to the high costs of electricity production in NIIs and the stable and reliable supply of electricity in NIIs are the hybrid systems. The re-structuring of the existing power systems in combination with the penetration of RES will be an effective solutions to autonomous power systems. The scope of this thesis is to examine the feasible and viable infrastructure of a hybrid system using as case study the island of Donoussa in terms of cost effectiveness , the reduction of emissions and the reliable supply of electricity. The load profile of the island was provided by HEDNO (Hellenic Electricity Distribution Network Operator S.A.) and the software that is used for this study is HOMER software. Different scenarios which include conventional units of the existing power system, PV panels, Wind Turbines, battery storage and converters are studied in order to achieve 20%, 50% and 100% renewables adoption in respect to the most effective Excess Electricity rate, NPC (Net Present Cost) and LCoE (Levelized Cost of Energy).

1.2 Literature Review

Because of the broad research and applied interest towards hybrid renewable energy systems, a wide range of published literature and work carried out can be met on this field. There are studies that examine the optimal design of a hybrid system via HOMER software for Greece. Study in Ref. [5] presents an analytic overview of the autonomous electricity systems of Greek islands and different scenarios of re-structuring the autonomous electrical system of Astypalea. The main aim of the energy optimization of this study is to reduce energy production costs in a sustainable way. Authors in Ref. [6] present the sustainable planning of a renewables-based energy system with the scope of replacing the existing diesel generators with a wind-pv-hydrogen hybrid system in Karpathos island, Greece. In addition, in [7] authors examine the possibility of utilizing a RES-hybrid system for a small Greek island (Agios Efstratios) by exploring three different case scenarios. They aim in the optimal design of the microgrid with the less effective cost through an techno-economic analysis. A study on the island of Lesvos [8] researches the pumped hydro storage renewable energy system by the use of a computational algorithm, concluding that 25% of the islands energy demand can be economically met by renewable energy systems. All studies mentioned above used HOMER software for optimization and simulation. Furthermore, the technical - economic details of a hybrid power plant, towards 100% electricity production for the autonomous island of Sifnos, Greece, following the initiative of the Sifnos Island Cooperative (SIC) to claim the island's energy independence and a sustainable future for the local community is presented in paper [9]. The Ref. [10] refer to a HRES in Fournoi island, in eastern Aegean sea, is designed in order to utilize hydropower for electricity generation and cover drinking and agricultural water demands through desalination of sea water. The operation of a hybrid power stations that contain advanced sodium sulfur (NaS) batteries as storage medium in the autonomous power system of Samos Island is studied in Ref. [11]. A flexible power plant is modelled in [12] associated with a Multi-Objective Particle Swarm Optimization in order to obtain the optimal size of each plant component and the configuration located in Tilos islands, Greece. Finally, in Ref. [13] the energy modeling and the life cycle analysis of a generic hybrid power system installed in the island of Crete, Greece is presented.

Besides Greece, there are many studies that examine the feasibility on hybrid energy systems on islands all over the world. Ref. [14] through HOMER software examines the most cost effective configurations of a hybrid autonomous energy generation system in St. Martin's island in Bangladesh. Moreover, Ref. [15] and [16] highlight a hybrid system composed of solar PV, wind turbines, diesel generators, micro-hydro plant and batteries in order to supply the electricity demand of the Calayan island in Philippine and for Fiji islands respectively. In Ref. [17] the technical and economical viability of of hybrid energy system in the Masirah Island power system in Oman is examined through HOMER and DIgSILENT software. A study in Ref. [18] discusses the techno-economic evaluation of a 100% renewable hybrid system on a remote island. The research [19] proposes a mathematical model to analyze the effect of varying saturation for a hybrid PV-wind-battery system for Jiuduansha island near Shanghai. Moreover, authors in [20] use linear programming or optimal design of hybrid power generation system (HPS) in which conventional units and renewable energy generators are incorporated to supply electricity to islands isolated from the national grid. The paper [21] presents a hybrid system implementation planning as the results of optimal sizing and operational strategy of hybrid PV-Diesel-battery storage system at Sebira Island, Kepulauan. Authors in Ref. [22] design a hybrid wind-solar-fuel cell power plant and a power managements strategy is proposed for TUNeIT [TUNisia and ITaly] Project, that involves the realization of four artificial islands to connect Bon (Tunisia) and Pizzolato (Sicily). Besides the off-grid and autonomous applications, grid-connected hybrid systems are examined. Ref. [23] proposes an optimal off-grid and a grid-connected hybrid system to cover the load demands of Bozcaada island, Turkey.

As mentioned earlier hybrid systems provide electricity not only in islands but in remote areas, communities, houses and buildings (schools, university campus, etc.). Fortuitously, remote areas generally are rich in locally available renewable energy resources. Ref. [24], [25], [26] and [27] examine microgrids for the support of university building, academic institution, university campus and of an electric machinery laboratory. Techno-economic analysis and optimum design of a hybrid grid-independent system for the residential and agricultural electric load requirements of an energy poor community of Yamunanagar district in the State of Haryana, India is examined in [28] through MATLAB/Simulink and HOMER software. Ref. [29] uses a new metaheuristic algorithm called Cuckoo Search is applied for solving the hybrid energy system optimization problem in a remote area located in Almora district of Uttarakhand, India. Ref. [30], [31], [32] and [33] make researches for the analysis of off-grid microgrids for the electrification of remote areas in Greece, Cameroon, Nigeria and Malaysia.

Some of the studies that described above were employed in remote areas with no access to electricity, others to support buildings and other for islands. The design of each hybrid system is different and is dependent on the available climatic data and load profile of the different case study. Besides, there are only a few studies which take into consideration for the optimum design and the techno-economic analysis for the hybrid system the excess electricity factor. Excess electricity is a very important parameter which defines the stability, the reliable supply of the system and the economic viability of a hybrid system. In Ref. [34] the authors aim to investigate the existence of excess electricity in an isolated hybrid system in Nepal and discuss the impact of excess electricity on hybrid system's cost and performance. To address aforementioned literature flaw, this thesis targets to the optimal design of hybrid system for a not-interconnected island in Greece (Donoussa) with the minimum percentage of Excess Electricity and the most cost-effective NPC and LCoE. In addition, Donoussa island has higher energy demands from most of the cases that presented above, with a population of 167 inhabitants. This study examines three scenarios of utilization of a hybrid system according to renewable adoption rate. Techno-economic analysis ensure the technical and economic viability of the hybrid system.

1.3 Thesis objective

The main objective of this thesis work is the design of an off-grid, autonomous hybrid system/microgrid for the electrification of Donoussa island, Greece. Based on the load profile of Donoussa island (provided by HEDNO) different schemes/scenarios of hybrid renewable energy systems will be examined including diesel generators (conventional units of the existing power system), PV panels, Wind turbines, battery, converter with different percentages of renewable energy sources penetration of each scheme. The hybrid system will be feasible and cost effective to satisfy the load demands of Donoussa through system design simulation and optimization. Furthermore, comparison will be applied between hybrid system configurations for the selection of the optimal system configuration of each scenario based on Excess Electricity parameter, NPC cost and LCoE. A sensitivity analysis will be conducted in order the system performance to be examined in different conditions. The goal is the achievement and the proposition of optimal hybrid systems in terms of reliable power supply and cost.

1.4 Thesis Layout

Chapter one gives the background, reviews the related work and bibliography, introduces the thesis objective and describes thesis layout. The literature review is normally based on applications and optimization methods of hybrid systems all over the world. Chapter two analyzes different hybrid systems/microgrid configurations and describes briefly HOMER software. Scenarios, Modelling and Optimization of the hybrid system, which include the methodology of the optimization, electrical load data, wind and solar data, sizes and costs of all components as well as economic inputs, constraint inputs, and sensitivity variables are described in Chapter three. In Chapter four are examined optimization results of the different scenarios, then sensitivity analysis results are analyzed and Excess Electricity assessment is presented. Finally, in Chapter five are included the final conclusions and some suggestions for future work.

Chapter 2

Hybrid Systems/Microgrids and HOMER Software Tool

Hybrid system is defined as the combination of two or more renewable/non-renewable energy sources (like diesel generators, PV panels, Wind turbines). In addition, the basic components of the hybrid system include energy sources (AC/DC), AC/DC power electronic converters and load as wells as energy storage like batteries, flywheels, pumped-storage hydro. [35] In the case renewable energy sources generate power that exceeds the energy load demands, surplus power is used in order to charge the battery. In contrast due to intermittent nature of renewable energy sources when the power from renewables is insufficient to meet the load, battery and conventional machines are used as back-up resources to meet the load demands. Hybrid Renewable Energy Systems (HRES) have the capability to operate in stand-alone mode/islanded/off-grid and on the other hand on-grid/grid-connected. In grid-connected mode HRES are used in places like universities, hospitals, factories and town. In on-grid situations when grid electricity prices are low the HRES meets the load from the grid and charges the energy storage with renewable resources. In contrast when the prices are high, the load is met with the HRESs resources and sells the extra energy to the grid. [36] As for Hybrid systems in an stand-alone mode, are used mostly in remote, rural areas and islands. A HRES in a stand-alone mode is a appropriate mean to provide electricity areas where grid extension is difficult, costly and electricity transmission from centralized utility is difficult. For islands and remote areas HRESs are able to generate electricity in a sustainable way and make comfortable people's standard of living. As it mentioned earlier HRES use both renewable energy sources and conventional diesel generators in order to ensure the viability, reliability and affordability of the supply. Drawbacks are observed of using renewable sources exclusively as off-grid/stand-alone power systems or conventional generators (intermittent nature of RES, fuel costs, high transportation fuel costs, climate change). So HRESs use a combination of both conventional and RES with a lot of advantages like diesel fuel reduction as well as the reduction of greenhouse gas emission, increase of penetration of renewables, the exploitation of locally available resources, decrease in the CoE (Cost of Energy) and electricity access in remote areas and during periods waiting for grid extension or grid damages. In this particular study a stand-alone hybrid system is going to be studied for the island of Donoussa (an off-grid Greek island) which consists of diesel generator, wind turbine, PV panels, batteries and a converter. Some of the components generate AC and others DC power directly.

2.1 Hybrid Systems Configurations

Hybrid energy systems designs can be categorized according to their voltage and their load demands in different configurations. The main configurations for hybrid energy systems are 3: DC coupled, AC coupled and mixed-coupled hybrid power systems.

2.1.1 DC-coupled configuration

In the direct current configuration, all the energy conversion systems are connected either directly or through a DC/DC power converter, to a DC bus line to which the DC loads are connected. All the AC power sources are converted to DC power sources through converters. In addition, this configuration is able to support and supply AC power to the AC loads through a DC/AC converter. As far as energy storage of the hybrid system is concerned, is also connected to the DC bus line through a bi-directional converter in order to meet the energy needs to the DC loads in response to the demand. Main merits of DC coupled configuration is that there is no need for the synchronization of the system that can be used for DC micro-grid and that the demand is satisfied without interruptions. Despite the merits, there is a main disadvantage in the conversion system. If there is a failure in the DC/AC converter the whole system could not supply AC power to the AC loads. A typical DC-coupled configuration can be seen in Figure 2.1. [2] [37] [38]

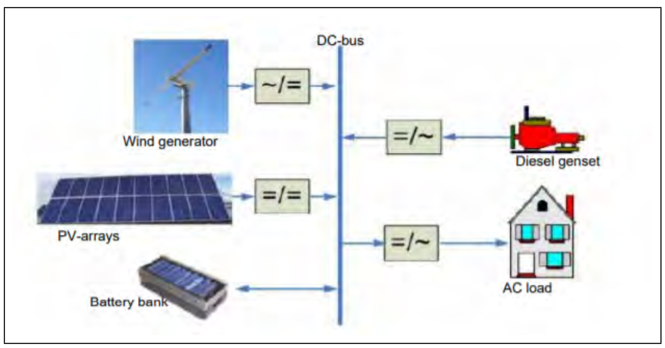

Figure 2.1: DC-coupled configuration. [2]

2.1.2 AC-coupled configuration

In this configuration all the components (generating and storage technologies) of the hybrid system are connected to AC bus line either directly with the loads or in line with the loads. Moreover, there are two subcategories for the AC-coupled configuration of hybrid systems which are: centralized AC coupled hybrid systems and decentralized hybrid systems.

2.1.2.1 Centralized AC-coupled

In Centralized AC-coupled all components are connected directly to AC bus line before they are connected with the loads. Generating components are able to be connected either directly to the main AC bus line or through a AC/AC converter. For the control of the battery a master inverter is required and DC electricity can be succeeded with the help of batteries. Figure 2.2 depicts a centralized AC coupled configuration. The main advantage of centralized AC-coupled hybrid system is that battery life is expanded due to the presence of central control system for the overcharging and deep discharging. Furthermore, it is also compatible with utility grids and the surplus electricity is able to be exported during minimum load demands. [2] [37] [38]

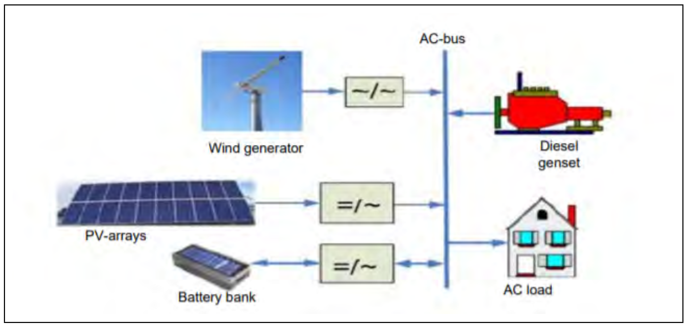

Figure 2.2: AC-coupled centralized configuration. [2]

2.1.2.2 Decentralized AC-coupled

In this type of architecture energy conversion systems are not connected to any of the bus, in contrast are connected individually directly to the load. Energy sources is not mandatory to be located near to each other but are able to connect to the load from where renewable energy sources. Merit of configurations like this is that the components that generate power are able to be installed directly from the location renewable energy sources are available. On the contrary drawback can be observed in such decentralized AC-coupled systems to the power control of the system which can be face difficulties. Centralized system is preferred due to the controllability that presents. In Figure 2.3 can be seen decentralized AC-coupled system. [2]

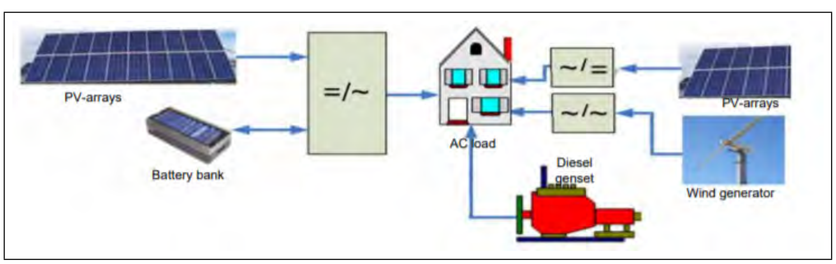

Figure 2.3: AC-coupled decentralized configuration. [2]

2.1.3 Mixed-coupled configuration

Mixed coupled configuration is a mix of DC-coupled and AC-coupled configuration. Some components like PV panels along with the battery (energy storage) are connect to DC bus line while other renewable energy components are connected to AC bus line along with conventional machines like diesel generator. In Figure 2.4 can be observed a mixed-coupled configuration of a hybrid system. [2]

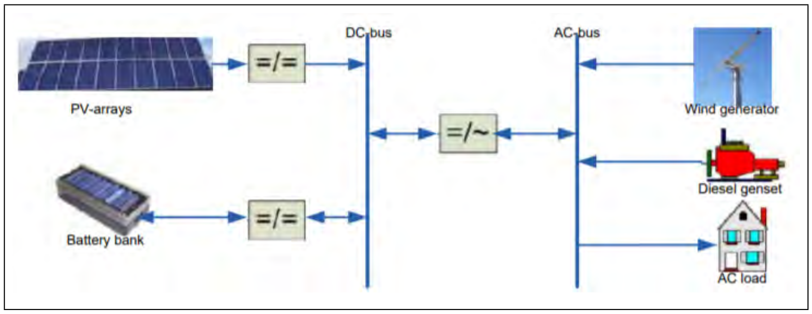

Figure 2.4: Mix-coupled configuration. [2]

2.1.4 Series/parallel Hybrid Systems

Another categorization for microgrids/hybrid systems is based on the type of the supply provided by diesel generators and renewable energy sources. The two categories that emerge are series and parallel hybrid microgrids.

2.1.4.1 Parallel Hybrid systems

In parallel hybrid power systems configuration, AC components like wind turbines and diesel generators supply power directly to the consumers. Some of the merits of this configuration are the greater diesel efficiency, the decrease of the cost of diesel and the capacity of battery and the possible optimal generation. Parallel hybrid power systems are divided into two sub-categories: DC-couple systems and AC-coupled systems. These two categories were already discussed in subsection 2.1.1 and 2.1.2 respectively. [2]

2.1.4.2 Series Hybrid systems

The main characteristic of this configuration is that DC power that is generated from the components is directly supplied to the battery. As a result of this all the generated power from PV panels, wind turbines and diesel generators is used to charge the battery. A charge controller is responsible and connected with each component except the diesel generator which is equipped with a rectifier. The AC demands of the loads are satisfied with the help of an inverter which converts DC power into AC power. Deep charging of the battery bank is avoided due to the presence and operation of the charge controller, which also ensures that battery is not overcharged from PV panels and wind turbine. Another name for this topology is centralized DC bus configuration. This name is justified from the fact that all sources are connected to DC bus line and the load is fed through a single point. Figure 2.5 shows such a configuration. Despite the simple configuration of these systems there are some drawbacks. The efficiency of the system is decreased due to the fact that all power is stored in the batteries. In addition, continuous charging and discharging reduce battery lifetime and the power control of diesel generator is difficult as the main purpose of diesel generator is the charging of battery. [2]

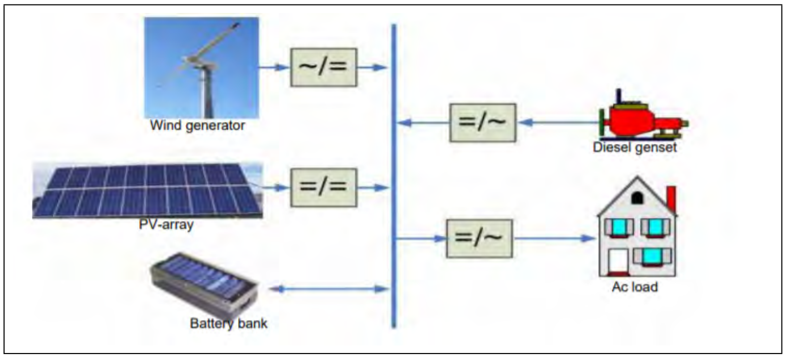

Figure 2.5: Series hybrid system configuration. [2]

2.2 Modelling Software: HOMER Pro

HOMER is considered to be a powerful tool which is suitable for the design of HRES (Hybrid Renewable Energy Systems) and carry out techno-economic analysis in order to determine through this optimal size of its components. HOMER is a software which has been developed by National Renewable Energy Laboratory (NREL), United States. Wind turbines (WT), PV array, fuel cells, small hydropower, biomass, converter, batteries and conventional generators are some various resources that HOMER software is able to model. Furthermore, this software considers HRES in grid connected and off-grid power systems and uses the NASA (National Aeronautics and Space Administration) weather database for the measurements of the renewable devices that user is able to add to the system.

For this particular study the software version of HOMER that is used is HOMER Pro (version PRO x64). HOMER software is composed of 3 major features which are Simulation, Optimisation and Sensitivity Analysis. Regarding Simulation, techno-economic calculations are offered from this tool and more specifically offers calculations as the Net Present Cost (NPC), initial Capital Cost (CC), Cost of Energy (COE) produced, Cash Flow, Renewable Fraction of energy consumed by the load, Grid Import and Export rates and many more. As for Optimisation, HOMER gives the user the opportunity to determine the best solution of performing system according to the inputs. Through a great number of simulations of different components tool gives the best feasible solutions. Another one major feature of HOMER is Sensitivity Analysis. Real values of some parameters of the system might deviate from the values of the simulated system parameters. Sensitivity analysis is defined as the the measurement of performance of an estimation for different inputs, so the users are able to examine and test the designed system with different initial values and conditions. HOMER has a large number of inputs as climate data, electrical load, technical and economic parameters of the equipment used for generation and storage, sensitivity variables, dispatch strategy, and some more constraints. Then software simulates the operation of the system, calculating the energy balances for each one of the 8760 hours of the year, resulting in the the optimal system size and control strategy based on the lowest net present cost (NPC). [36] [39]

Chapter 3

Modelling and Optimization of the hybrid system

3.1 Donoussa island Background

3.1.1 Study Area

Greece is a country with a great numbers of islands, approximately 6000. Islands are the main morphological feature of Greece and only 227 of the 600 are habitable. Coastline of Greece is about 13,676 km.

Donoussa island is a small Greek island which is situated in the Aegean sea, in the southeastern Cyclades, 10 miles north of Amorgos and east of Naxos. The island is about 14 square kilometers, has a diameter of almost 5.5 kilometers and has a maximum altitude of 385 meters. Donoussa's permanent population is 167 according to last census and is considered to be a popular tourist destination especially during the summer months and as a result of this the energy demands of the island are increased during the summer. The main occupation of the permanent habitants of Donoussa is fishery and livestock. Donoussa island consists of 4 settlements (Donoussa, Mersini, Charavgi and Kalotaritisa). In addition, the first inhabitants which settled on the island came from the island of Amorgos and founded the village of ”Stavros”. Donoussa is administratively part of the Naxos municipality. In Figure 3.1 can be seen a characteristic view of the main settlement of Donoussa.

3.1.2 Power system of Donoussa

As for the power system of Donoussa, the island is one of the 32 non - interconnected Greek islands. The peak hours according to HEDNO (Hellenic Electricity Distribution Network Operator) for the island are 11:00 to 14:00, 18:00 to 21:00 during winter and 10:00 to 14:00, 18:00 to 23:00 during summer. As it mentioned earlier Donoussa is a tourist attraction so energy needs and peak hours increase during the summer. The energy system of Donoussa is basically based on one main thermal plant and as a result for the production of electricity, diesel oil is used. Until now no RES (Renewable Energy Sources) are used for production in the island of Donoussa. The types of generators and their characteristics of the thermal plant

Figure 3.1: View of the main settlement of Donoussa [pigi]

can be seen in the Table 3.1. The sum of output power of all generators is 0.940 MW. The total production of the thermal plant of the island for electricity for the year 2017 according to HEDNO was 1012.66 MWh. In addition, the average annual variable cost of conventional units of the Donoussa power system is equal to 250.02 €/Mwh for 2017. Indicatively, it is reported that for 2017 the average weighted annual diesel purchase cost ranged to 796.40 €/klit and the average annual additional operating and maintenance costs are estimated for each unit and equal to 4.04 €/MWh. The total operating and maintenance costs for the conventional system power plant was 662.71 €/MWh. Furthermore, the total load for the year 2017 was 1263 MW. Finally, no RES are used for the energy demands of Donoussa, so a hybrid system would be a great solution for the island.

Table 3.1: Types of generators and their characteristics of Donoussa thermal plant provided by HEDNO.

No.	Type of Generator	Fuel	P_{max} (MW)	P_{min} (MW)
1	MAN D2566ME	DIESEL	0.080	0.045
2	MAN D2566ME	DIESEL	0.080	0.045
3	MAN D2566ME	DIESEL	0.080	0.045
4	VOLVO PENTA TAD 1345GE	DIESEL	0.250	0.100
5	VOLVO PENTA TAD 1345GE	DIESEL	0.250	0.100
6	VOLVO PENTA TAD 740GE	DIESEL	0.200	0.110

The hybrid system that is proposed in this study has main objective to meet the load demands for the yearly load of Donoussa island. The renewable energy sources that are used from the hybrid system in this thesis are wind and solar energy, in contrast diesel generator and batteries for energy storage are used in order to be controlled the intermittent nature of renewable energy sources. PV panels generate DC type output voltage while diesel generator and wind turbines generate AC output voltage. In addition, there is a bidirectional converter with a main purpose to charge the battery by changing AC voltage to DC voltage. Furthermore, provides alternating type current back from battery to consumers when there is such a need. The load of the residents of the island is considered to be of AC type. Next sections of this chapter are referred to the input variables that are necessary for the smooth optimization and modeling of the system and explain some values which are related to the inputs.

3.2 Donoussa electricity load

In HOMER modelling tool the first parameter that has to be imported and the most important one is the electricity load which is next to the selection of the components from the library of HOMER software. As for the electric load profile for Donoussa island, electric load was possible to be retrieved by HEDNO (Hellenic Electricity Distribution Network Operator S.A.), at an hourly base for the year 2017. A text file with 8760 values was imported in HOMER software. The diurnal variation of the primary load profile of Donoussa island is depicted in Figure 3.2. As it can be seen, the load increases during summer months July, August and then September due to the tourism which is intense in the island. These months load is high around 12:00 which may be caused due to the air - conditioning loads and afternoon from 18:00 to 23:00. In addition, Figure 3.3 shows the annual electric load of Donoussa where it is depicted that during August there is a peak in the electrical load of 450 kW, more specifically at 12 of August at 22:00. Typically the increases of load are observed during the period from July to September. The average consumption of the island is 3460.30 kWh/day and average load is 144.18 kW.

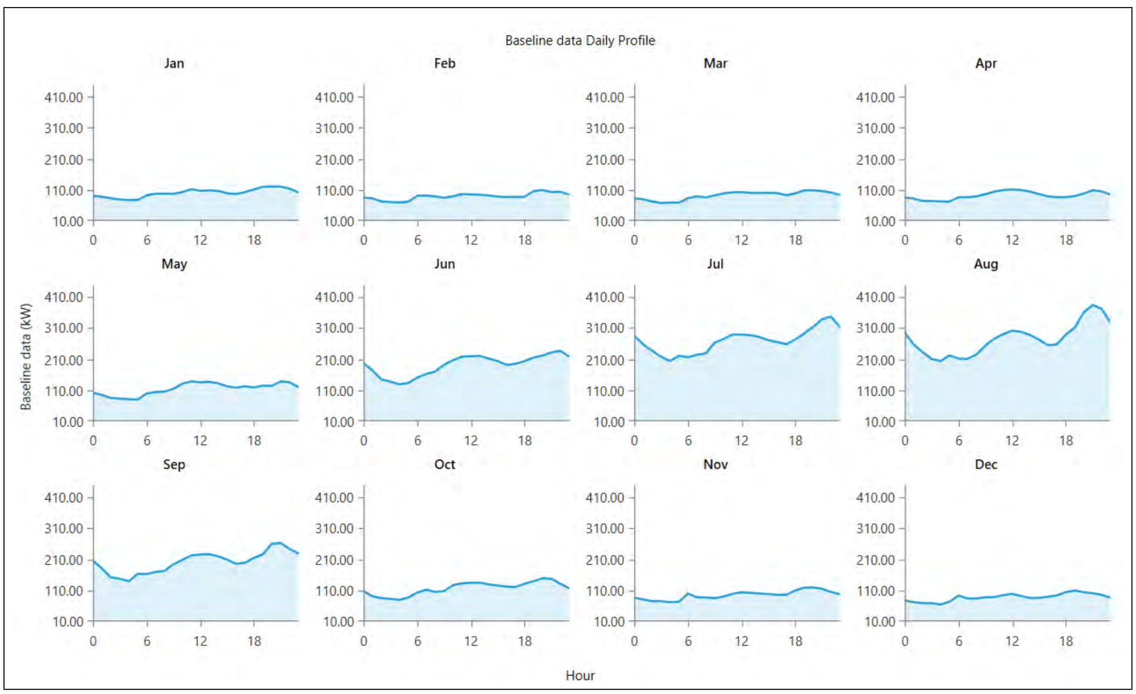

Figure 3.2: Diurnal variation of electrical load profile.

Moreover, the variation of the electricity load during the day is indicated in Figure 3.4. 0 to 100 kW are observed during night hours 0:00-6:00 hours. Then peak hours during winter are 11:00 to 14:00 and late afternoon hours 18:00 to 21:00. During summer daily peak load occurs 10:00 to 14:00 and afternoon from 18:00 to 23:00. Furthermore, Figure 3.5 depicts the seasonal profile and it clearly observed that during months July, August and September the electrical load is increased and as it mentioned earlier it is due to the tourism on the island.

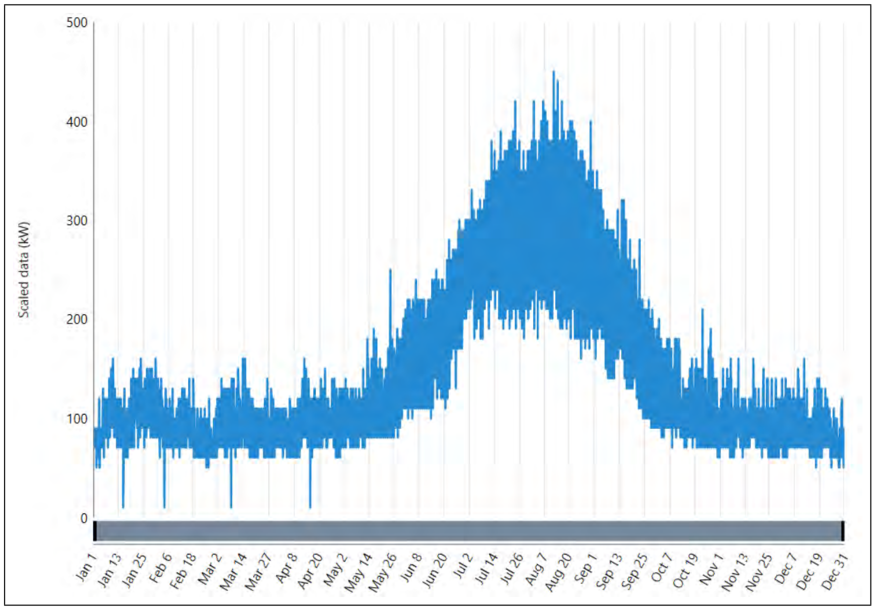

Figure 3.3: Annual load of Donoussa.

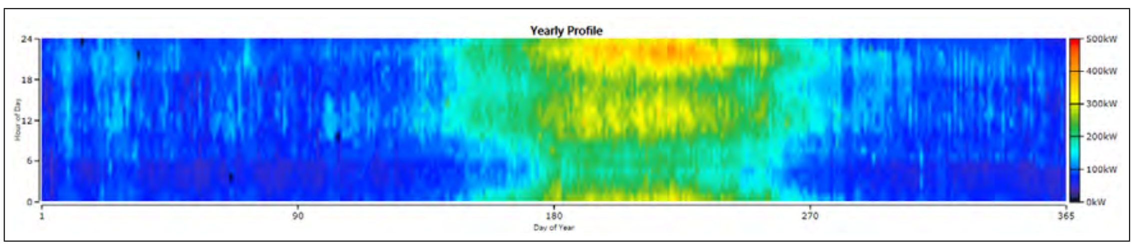

Figure 3.4: Data-Map of the monthly load profile.

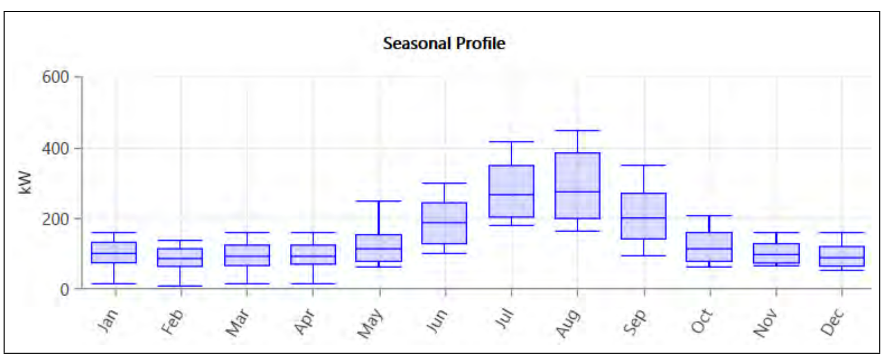

Figure 3.5: Seasonal load profile of Donoussa.

3.3 Solar irradiation data and Wind resource assessment

3.3.1 Solar irradiation data

Greece as it mentioned earlier has a great potential for solar power. Below in Figure 3.6 can be seen the map with the average annual sum of global horizontal irradiation (GHI) for

Greece from 1994 to 2016. Solar irradiation in the island of Donoussa is in high levels. For solar irradiation data there are two ways for the input in HOMER software. Firstly, HOMER gives the opportunity to retrieve solar data automatically from NREL's and NASA's satellite databases for the specified latitude and longitude via a connection to Internet. The second way HOMER software offers regarding solar data is that solar irradiation can be imported, with time steps of many sizes between 60 minutes and one minute in a text file.

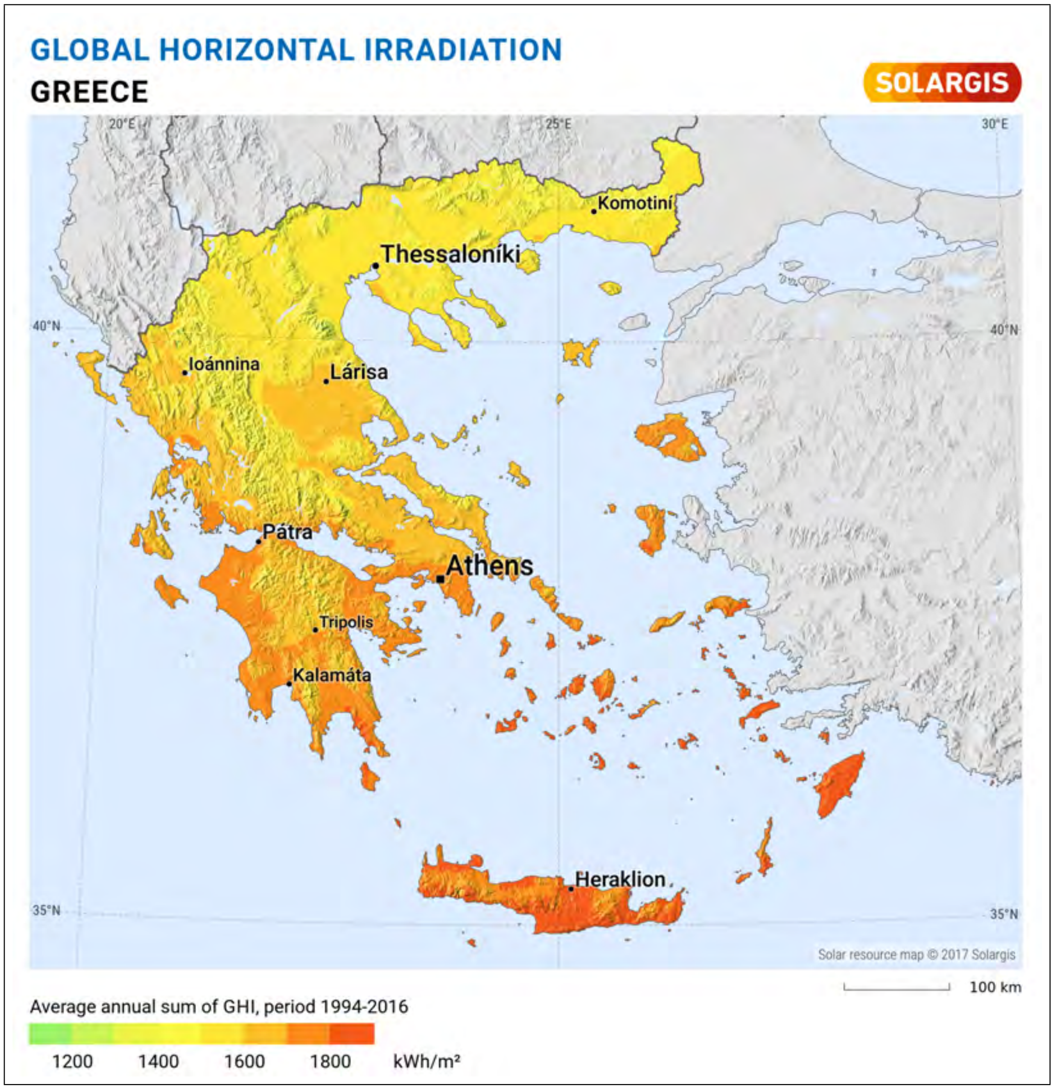

Figure 3.6: Global Horizontal Irradiation, Greece 1994-2016. [3]

The daily radiation per month was imported to HOMER software. Global horizontal irradiation data were retrieved from the Photovoltaic Geographical Information System for year 2016 for Donoussa island (latitude is 37.10656, longitude is 25.81385). The annual average solar global horizontal radiation is 5.42 kWh/m^2/day. The solar radiation data can be seen in the Table 3.2 below. In Figure 3.7 is depicted Monthly Solar Radiation Sources and Clearness Index and can be concluded that solar resources are abundant during the whole year so a great amount of electricity could be generated from PV panels. As it is visible from the Table 3.2 June was the sunniest month with 8.467 kWh/m^2/day of daily radiation and the minimum value of daily radiation was 2.181 kWh/m^2/day in December. In addition, clearness index is a measure of the clearness of the atmosphere and indicates the solar radiation that is transmitted to earth's surface. The value of clearness index varies between 0 to 1. In this study the maximum value is 0.726 in April and the minimum value of the index is 0.494 in January. In general, Donoussa is considered to be a great place for solar resources in order to generate electricity.

Table 3.2: Donoussa monthly average solar radiation data.

Month	Clearness Index	Daily Radiation kWh/m^2/day
January	0.494	2.339
February	0.617	3.759
March	0.651	5.194
April	0.726	7.133
May	0.658	7.290
June	0.732	8.467
July	0.725	8.194
August	0.717	7.355
September	0.691	5.933
October	0.642	4.258
November	0.585	2.940
December	0.506	2.181

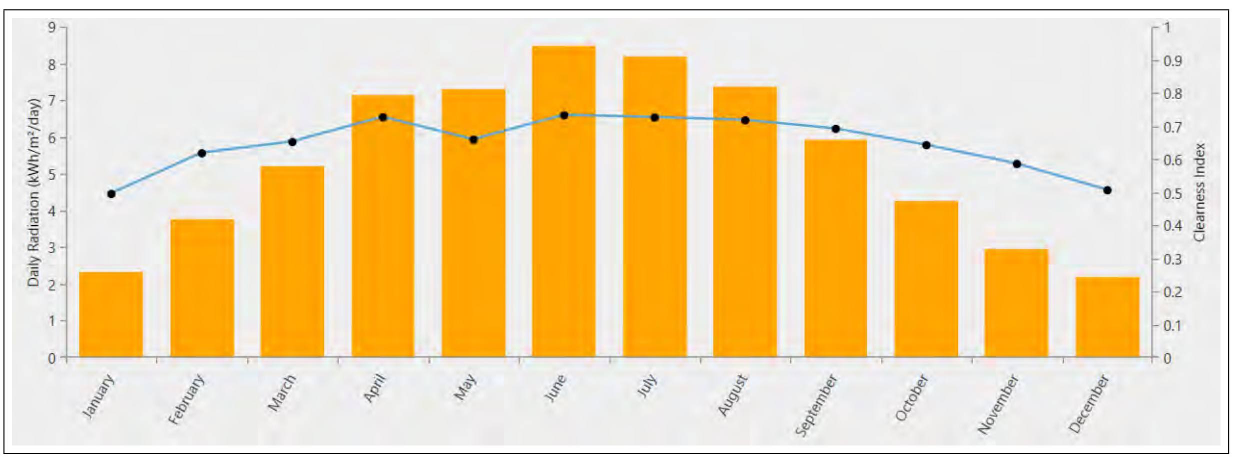

Figure 3.7: Monthly Solar Radiation Sources and Clearness Index.

3.3.2 Wind resource assessment

As it mentioned earlier Greece is a country with great wind energy potential. Wind speeds are high throughout the year all over the country, in mainland and especially in islands. In Figure 3.8 can be seen the wind map of Greece where, in most areas the wind speeds are high. As for this study, Donoussa island is considered to be an ideal location for wind applications and as can be seen the from the wind map of Donoussa in Figure 3.9 mean annual wind speeds vary from 6-7 m/s to 10 m/s.

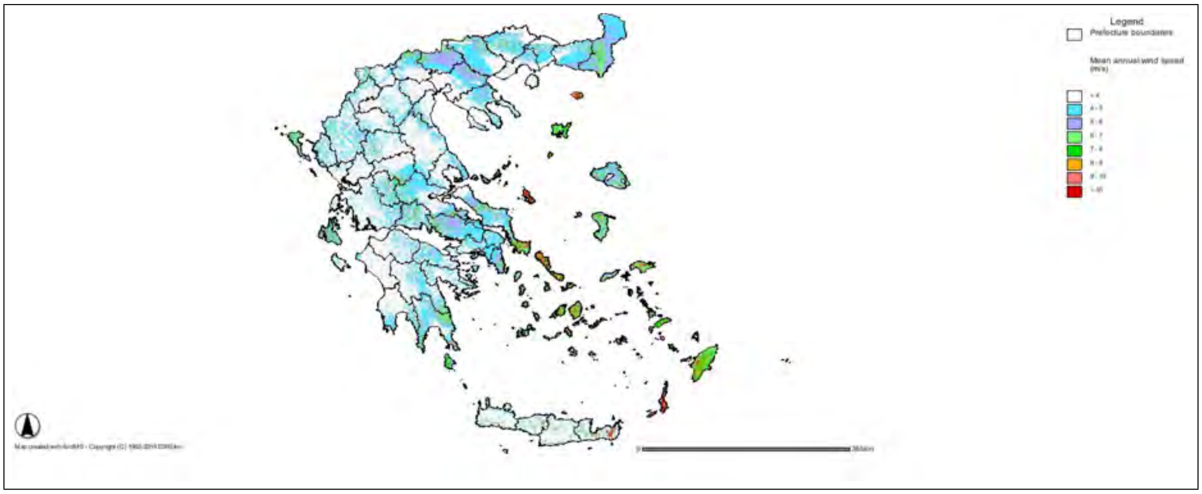

Figure 3.8: Wind map of Greece, CRES. [4]

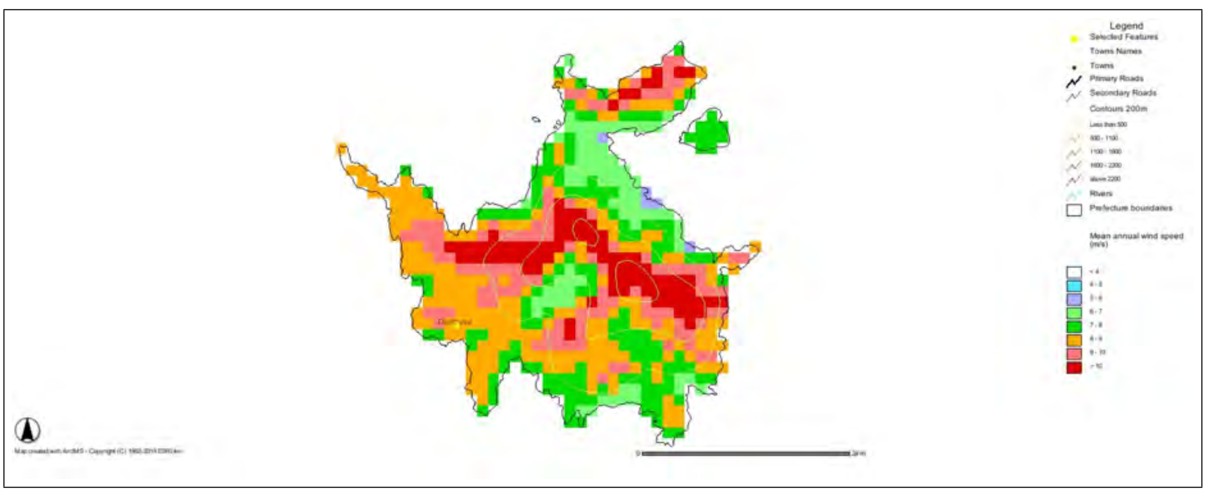

Figure 3.9: Donoussa wind map, CRES. [4]

Similar to solar resources, wind speeds were measured in order to be imported into HOMER software. Wind speed at 50 m above ground level were measured from NASA Prediction of Worldwide Energy Resource (POWER). Table 3.3 below shows the average monthly wind speed of Donoussa. The average annual wind speed is 7.10 m/s. Inputs of monthly average wind speed in HOMER resulted in the comprehensive Figure 3.10. Finally, wind speeds are sufficient for electricity generation from wind turbines and there is a great wind energy potential on the island.

Table 3.3: Donoussa monthly average wind speed data.

Month	Average Wind speed (m/s)
January	8.250
February	7.080
March	7.950
April	5.200
May	5.880
June	5.560
July	6.680
August	8.250
September	8.000
October	6.380
November	8.250
December	7.720

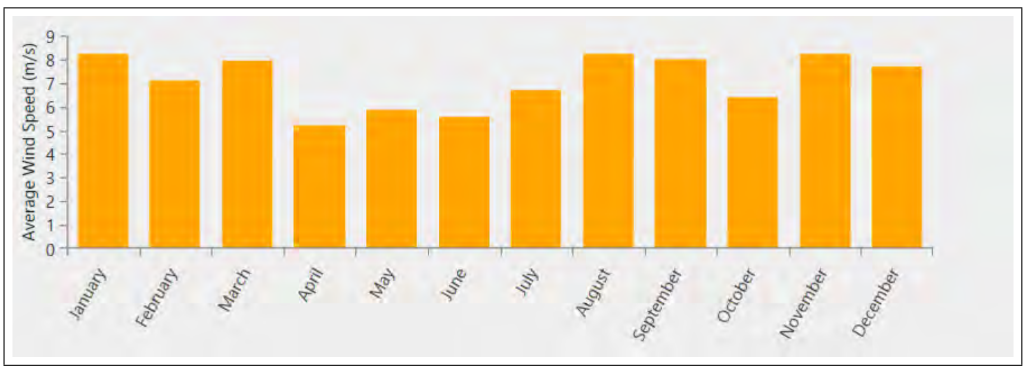

Figure 3.10: Average monthly wind speed of Donoussa island.

3.4 Simulation systems - Scenarios

HOMER software after the simulation of different configurations of energy system components, ends up and displays to the user for extended analysis only the feasible power schemes scenarios. As it mentioned earlier, this study is to propose a renewable hybrid system/microgrid in order the current conventional fossil fuel power system of Donoussa island to be substituted without causing stability problems in the network. Moreover, the simulation study will be performed on different scenarios in order the effectiveness of adding RES and storage (batteries) in the existing power system of Donoussa as well as a 100 % RES hybrid system/microgrid with storage to be verified. The decrease of the the diesel generators operation and use is an important aspect that this thesis studies. The power system of Donoussa island is composed of 6 diesel generators with total power of about 940 kW which is almost twice as large as the peak load of the system (450 kW). The peak load and the high load demand lasts only for a specific time of year (summer) and the rest of the year the average load demand is smaller. As a result of this the power system of Donoussa can be considered oversized power system. To that end, in this study 3 main scenarios were formulated for the electrification of the island of Donoussa.

The first scenario includes Wind turbines, PV solar panels and five diesel generator units. The renewable fraction of this scenario is considered to be 20%. In the Figure 3.11 below can be seen the configuration of this scenario.

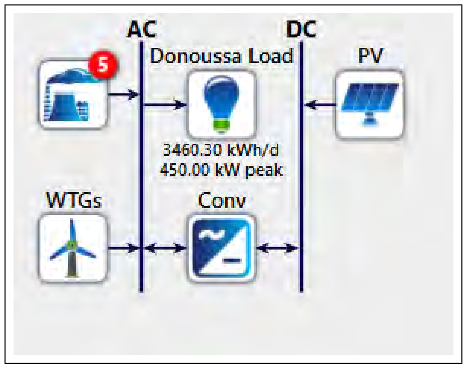

Figure 3.11: Wind-PV-Diesel Scenario.

As for the second scenario the operation of three diesel generators are dismissed and only three diesel units (200 kW, 250 kW and 80 kW respectively) operate along with wind turbine generators, PV solar panels and battery with a renewable fraction of 50%. Figure 3.12 depicts the microgrid configuration of the second scenario.

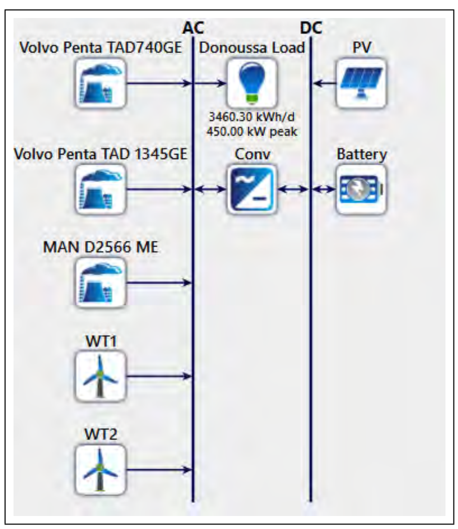

Figure 3.12: Wind-PV-Diesel-Battery Scenario.

Finally, in the last scenario it was attempted the feasibility of the system only with RES (Renewable Energy Sources) production without the operation of conventional units. The hybrid system/microgrid consists of Wind turbines, PV solar panels and battery bank. As it is easily understood the renewable fraction of this scenario is 100%. Moreover, two sub-cases are going to be considered. In the first sub-case autonomy days of battery are going to be assumed five and as for the second sub-case three days are assumed. The configuration is depicted in the Figure 3.13.

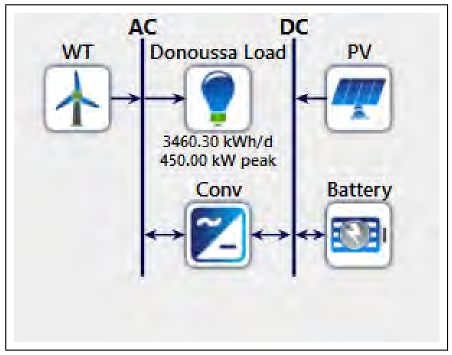

Figure 3.13: Wind-PV-Diesel-Battery Scenario.

3.5 Modelling, Cost data and Size specification of each component of Hybrid system

The main criterion of selection of the components of hybrid system of this thesis is cost. The should be selected with respect to the optimal cost as well as the quality. Moreover, one of the main purposes of this work is the optimum power system configuration that would meet the load demand with minimum NPC and COE. Three are the main costs that HOMER Pro software takes into consideration: Capital Cost, Replacement Cost and O & M (Operational and Maintenance) Cost. Capital Cost is considered to be the total installed cost of that component at the beginning of the project. [40] Replacement Cost is the cost of the replacement of one component at the end of its lifetime. This cost could be different from the Capital Cost for many different reasons, at the end of their lifetime is not mandatory a component to be replaced. Replacement Cost is stable if a malfunction occurs while initial Capital Cost may be eliminated or reduced by a donor organization. In addition, fixed costs in Capital Cost travel cost or other fixed costs are counted in contrast with Replacement Cost where are not accounted. Operational and Maintenance Cost is considered to be the sum of cost of each component of the system for its operation and its maintenance. Finally, in this section the sizes and costs of each component of hybrid system are going to be presented as well as some technical features of each component.

3.5.1 Solar Pv Analysis, Size and Cost

A solar cell is a semi-conductor device with main purpose to turn solar irradiance to electricity. PV array is modelled in HOMER software as a device that produces DC electricity using the global solar radiation in direct proportion. At first HOMER should take some inputs in order to calculate the output power from the PV array. Slope, azimuth and ground reflectance are the most important ones and the derating factor if the effect of temperature is applied. Slope is defined as the angle at which the panels are placed relative to the horizontal. Typically in fixed-slope PV systems with slope equal to latitude the PV energy production is nearly maximized, in this case 37.10 °. The azimuth is considered to be the direction that PV panels face. For south is 0 °, for north is 180 °, for east is -90 ° and for west is 90 °. PV panels are oriented towards the equator with fixed-azimuth panels and the azimuth is 0 ° in the northern hemisphere and 180 ° in the southern hemisphere. Moreover, ground reflectance is the fraction of solar radiation on the ground that is reflected. On tilted PV panels, this value is used for the calculation of the radiation incident. This value varies from 3% to 70% depended on the ground cover material and in this study is selected at 20 %. [23] When the effect of temperature is taken into consideration HOMER software calculates the power output of PV panels according to the following formula.

$$P_{pv} = W_{pv} \times f_{pv} \times \frac{G_T}{G_S} \times [1 + \kappa_p \times (T_C - T_{STC})] \tag{3.1}$$

where:
W_{pv} is the peak power output of the PV modules (kW),
f_{pv} is the PV derating factor (%),
G_T is the solar radiation incident on the PV module in a specific timeslot (kW/m^2),
G_s is the incident radiation number under standard test conditions (1 kW/m^2),
κ_p is the is the temperature coefficient of power (%/C),
T_C is the PV module temperature in the current hour (°C),
T_{STC} is the PV module temperature under standard test conditions (25 °C).
This present study assumes the effect of temperature on the PV array. In addition, as far the derating factor is concerned, is a scaling factor that is applied to the PV array power output in order to model output which is reduced, in real-world operating conditions in contrast with the ideal conditions under which the PV panel was rated. Real-world conditions are considered effects like soiling of the panels, wiring losses, shading, snow cover, aging, temperature, dust etc. The derating factor is selected to be 80 % as a result of this the production of PV panels to 20% in order to model the real-world condition of dust and temperature.

Another one important factor for the output power of the PV is the PV cell temperature which is the temperature on the surface of the PV array. The temperature during night is equal to the ambient temperature in contrast with daytime when temperature can be increased up to 30 °C. PV array energy balance can be seen in the following equation.

$$\tau \times \alpha \times G_T = \eta_C \times G_T + U_L \times (T_c - T\alpha) \tag{3.2}$$

where:
τ is the solar transmittance of any cover over the PV array,
α is the the solar absorptance of the PV array,
G_T is the the solar radiation striking the PV array,
η_C is the electrical conversion efficiency of the PV array,
U_L is the coefficient of heat transfer to the surroundings,
$T\alpha$ is the ambient temperature. The temperature of the cell can be seen in the formula below if the equation 4.2 is solved for T_c.

$$T_c = T\alpha + G_T \times (\frac{\tau \times \alpha}{U_L}) \times (1 - \frac{\eta_C}{\tau \times \alpha}) \tag{3.3}$$

The nominal operating cell temperature (NOCT) can help because the value of $\frac{\tau \times \alpha}{U_L}$ is difficult to be calculated. So the $\frac{\tau \times \alpha}{U_L}$ can be calculated as follows:

$$\frac{\tau \times \alpha}{U_L} = \frac{T_{c,NOCT} - T_{\alpha,NOCT}}{G_{T,NOCT}} \tag{3.4}$$

so T_c :

$$T_c = T\alpha + G_T \times (\frac{T_{c,NOCT} - T_{\alpha,NOCT}}{G_{T,NOCT}}) \times (1 - \frac{\eta_C}{\tau \times \alpha}) \tag{3.5}$$

HOMER software makes the assumption that value of $\tau \times \alpha$ is equal to 0.9 along with the assumption of the maximum power point operation of the PV array. According to these assumptions the cell efficiency is equal to the maximum power point efficiency as it can be seen in equation 4.6.

$$\eta_C = \eta_{mp} \tag{3.6}$$

$$\eta_{mp} = \eta_{mp,STC} \times [1 + \kappa_p \times (T_c - T_{c,STC})] \tag{3.7}$$

Power is affected by the temperature coefficient κ_p inversely. As cell temperature is increasing the efficiency of PV array decreases. Cell temperature can be written as follows:

$$T_c = \frac{T_\alpha + (T_{c,NOCT} - T_{\alpha,NOCT}) \times (\frac{G_T}{G_{T,NOCT}}) \times [1 - \frac{\eta_{mp,STC} \times (1 - \kappa_p \times T_{c,STC})}{\tau \times \alpha}]}{1 + (T_{c,NOCT} - T_{\alpha,NOCT}) \times (\frac{G_T}{G_{T,NOCT}}) \times (\frac{\kappa_p \times \eta_{mp,STC}}{\tau \times \alpha})} \tag{3.8}$$

After surveying different studies focusing on the cost provided, for this study the Generic flat plate was chosen with a PV panel of 1 kW. The cost of the PV panels is observed that varies in different studies and in different countries. The author considered the capital cost of PV at 620 €/kW, same price for the replacement cost. These costs include shipping, tariffs, installation, dealer mark-ups and insurances. Operation and maintenance cost are taken at 14 €/year. Lifetime of PV arrays is considered to be 25 years and tracking system is not included in the system of PV panels. The specifications for the chosen PV modules in this study are reported in Table 3.4.

3.5.2 Wind Turbine Modelling, Size and Cost

Wind turbines are machines that extract energy from a steam of air in order to convert it into mechanical energy and then this mechanical energy into electricity. This process is impossible not to have energy losses which are variable depending on the performance of wind installations. Mechanical power captured by a wind turbine can be seen in the formula below: [29] [33]

$$P = \frac{1}{2} \times C_p \times \rho \times A \times V^3 \tag{3.9}$$

Table 3.4: PV technical speciifications and costs.

Parameters (Units)	Value
Panel type	Flat plate
Derating factor (%)	80 %
Operating temperature (°C)	47 °C
Temperature coefficient	-0.5
Ground reflection (%)	20%
Lifetime (years)	25 years
Tracking system	No Tracking System
Capital Cost (€)	620 €/kW
Replacement Cost (€)	620 €/kW
Operation and Maintenance Cost (€/year)	14 €/year
Search Space Scenario 1	40, 50, 60, 70, 80, 90, 100 kW
Search Space Scenario 2	180, 190, 200, 210, 220, 230, 240, 250, 260 kW
Search Space Scenario 3 Case 1	1200, 1250, 1300, 1350, 1400, 1450, 1500, 1550 kW
Search Space Scenario 3 Case 2	1400, 1450, 1500, 1550, 1600, 1650, 1700, 1750 kW

where:
P is the mechanical power/kinetic power,
C_p is the power coefficient,
ρ is the air density,
A is the area swept by the wind,
V the speed of the wind.
Wind speed increases according to the height above the ground. The wind near surface is slowed due to the existence of ground-level obstacles such as vegetation, buildings and topographic features. Logarithmic profile and power law profile are used in order to express the wind speed. The power law profile is explained as given below:

$$\frac{U(h_{hub})}{U(h_{anem})} = \left(\frac{h_{hub}}{h_{anem}}\right)^{\alpha} \tag{3.10}$$

where:
$U(h_{hub})$ is the wind speed at the hub height of the wind turbine (m/s),
$U(h_{anem})$ is the wind speed at anemometer height (m/s),
h_{hub} is the wind turbine hub height (m),
h_{anem} is the height of the anemometer in meter (m),
α is is the power law exponent. A wind turbine starts to produce electricity when the wind exceeds a cut-in value and in case that the speed of the wind surpasses a cut-out value then the wind turbine stops the operation in order to be safely from serious damages. The power output of the wind turbine as follows:

$$P_{wt(t)} = \begin{cases} 0 & 0 \leq v \leq v_{cut-in} \text{ and } v \geq v_{cut-out} \\ \alpha \times v^3 + b \times P_{rated} & v_{cut-in} \leq v \leq v_{rated} \\ P_{rated} & v_{rated} \leq v \leq v_{cut-out} \end{cases} \tag{3.11}$$

The constants α and b are given by the following equations:

$$\alpha = \frac{P_{rated}}{v_{rated}^3 - v_{cut-in}^3} \tag{3.12}$$

$$b = \frac{v_{cut-in}}{v_{rated}^3 - v_{cut-in}^3} \tag{3.13}$$

where:
v_{cut-in} is the cut-in speed of the wind turbine (m/s),
$v_{cut-out}$ is the cut-out speed of the wind turbine (m/s),
v_{rated} is the rated speed of the wind turbine (m/s),
P_{rated} is the rated output power of wind turbine in kW.

The choice about the optimal wind turbine for the hybrid system of this study depends on many factors. First of all depending on the wind speed sources the contribution of the wind turbine power has to be sufficient, so a large wind turbine can be used in the hybrid system or a number of smaller wind turbines. In addition, the not particularly high load demand of the island, quantities of turbines, service time, hub height, cost of the component, type of electricity generated, cut-in wind speed are the restrictive values to select wind turbine. The selection of the wind turbine is going to be depended on the type of current. In this thesis an AC (Alternative current) is preferred in order to supply directly to consumers AC power. The wind turbines that are selected Eocycle EO20 and Aeolos-H 10kW. Rated capacities are 20 kW, 10 kW respectively for Eocycle EO20 and Aeolos-H 10 kW. According to different studies and market reports initial capital costs differ depending the study, the capacity of the wind farm (turbine size) and region. The capital cost varies from 1500 €/kW to 2250 €/kW. For this study the capital cost is selected at 1800 €/kW, the replacement cost is calculated almost at 80% of the initial capital cost. The operation and maintenance costs are assumed to be 3% of the initial capital cost. Table 3.5 and Table 3.6 below depict parametric inputs of wind turbine for HOMER software, some technical specifications and costs.

Table 3.5: Technical specifications and Costs of Eocycle EO20 Wind Turbine.

Parameters (Units)	Value
Model	Eocycle EO20
Nominal Capacity (kW)	20kW
Rotor Diameter (m)	15.8 m
Cut-in/out wind speed (m/s)	2.75 m/s - 20.00 m/s
Hub/tower height (m)	36 m
Capital Cost (€)	35800 €
Replacement Cost (€)	28640 €
Operation and Maintenance Cost (€/year)	1075 €/year
Scenario 1 Search Space	1, 2 units
Scenario 2 Search Space	1, 2 units

Table 3.6: Technical specifications and Costs of Aeolos-H 10kW Wind Turbine.

Parameters (Units)	Value
Model	Aeolos-H 10kW
Nominal Capacity (kW)	10kW
Rotor Diameter (m)	8 m
Cut-in/out wind speed (m/s)	3 m/s - 10.00 m/s
Hub/tower height (m)	24 m
Capital Cost (€)	17900 €
Replacement Cost (€)	14320 €
Operation and Maintenance Cost (€/year)	540 €/year
Scenario 2 Search Space	1, 2 units
Scenario 3 Search Space Case 1	1, 2, 3, 4, 5, 6, 7 units
Scenario 3 Search Space Case 2	1, 2 units

3.5.3 Diesel Generator Analysis, Size and Cost

Diesel generators are widely used in microgrids/hybrid systems as a backup power source with a main aim to improve the reliability of the system. A diesel generator is a machine which combines a diesel engine with an electric generator to produce electricity. The most important properties of a generator are its maximum electrical power output, its expected lifetime in operating hours, the type of fuel that it consumes along with the specific fuel consumption and the fuel curve that relates the quantity of fuel consumed to the electrical power produced. The fuel consumption of the diesel generator is related to the nominal power and output power of the diesel generator and can be seen in the equation below. [7]

$$F_{DG} = \alpha_0 \times P_{DG-rated} + \alpha_1 \times P_{DG-out} \tag{3.14}$$

where:
F_{DG} is the fuel consumption of the diesel generator in liters/h,
$P_{DG-rated}$ is the nominal power of the diesel generator (kW),
P_{DG-out} is the output power of the diesel generator (kW),
α_0 is the fuel curve intercept coefficient (L/h/kW),
α_1 is the fuel curve slope (L/h/kW).
Many time for different types of generators such as fuel cells and variable speed diesel engines, fuel curve is selected as a linear function of power production which is not appropriate. Usually for the common constant speed internal combustion generators, a straight-line in fuel curve representation is selected and is considered to be a a good choice.

In this thesis diesel generator for the hybrid system of Donoussa island will be used in two scenarios. As far as concerned the two scenarios (first one with diesel-wind turbines-PV and second one with diesel-PV-wind turbines-battery), the diesel generator is going to cover the RES and their unpredictable nature. Donoussa has already installed 6 diesel generators as it mentioned earlier and can be seen in Table. In addition, as for the scenario of Diesel-PV-Wind turbine-Battery hybrid system for simulations are selected the diesel generator, VOLVO PENTA TAD740GE (200kW) with a specific fuel consumption at 100% of

254.62 lit/MWh and VOLVO PENTA TAD1345GE with a specific fuel consumption at 100% of 283.63 lit/MWh. As for the scenario with no battery (PV-Wind turbines-Diesel) all the installed diesel generators of Donoussa's power system are going to be modelled and then through optimization will be decided which are going to be used. Thus the MAN D2566ME is modelled with specific fuel consumption at 100% of 270.1 lit/MWh. Diesel generators specifications and technical characteristics were imported in HOMER software. In general diesel generators are not allowed running under the minimum load ratio which in this study is assumed at 55% for VOLVO PENTA TAD740GE, 40% for VOLVO PENTA TAD1345GE and 56.25% for MAN D2566ME. Furthermore, the lifetime of diesel generators is measured in hours so it is not easy to estimate the lifetime of diesel generators because is directly linked with fuel quality and operating conditions. In this present study lifetime hours were assumed to be 15000 for VOLVO PENTA TAD740GE and VOLVO PENTA TAD1345GE and 10000 for MAN D2566ME. Diesel generator's VOLVO PENTA TAD740GE maximum power is 200 kW and its technical minimum / minimum power is 110 kW, as for VOLVO PENTA TAD1345GE the maximum power is 250 kW and its technical minimum / minimum power is 100 kW and for MAN D2566ME maximum power is rated at 80 kW while its technical minimum/minimum power at 45 kW. The capital cost is zero due to the fact that the units have been installed and have been already operating in the island. After surveying the diesel generator market, a replacement cost was assumed for VOLVO PENTA TAD740GE at 25000 €, according to similar models of this generator, replacement cost was considered for model VOLVO PENTA TAD1345GE at 38000 €and for the model of MAN D2566ME at 6000 €. In addition, the diesel price in Greece is 1.387 €/liter. Tables 3.7, 3.8 and 3.9 depict the characteristics and costs of diesel generators that are included in the simulations of the hybrid system.

Table 3.7: Technical specifications and Costs of VOLVO PENTA TAD740GE.

Parameters (Units)	Value
Model	VOLVO PENTA TAD740GE
Rated power (kW)	200 kW
Lifetime	15000 h
Minimum Load Ratio (%)	55%
Specific fuel consumption (100% load)	254.62 lit/MWh
Capital Cost (€)	0 €
Replacement Cost (€)	25000 €
Operating and Maintenance Cost (€/hour)	0.05 €/hour
Diesel Cost	1.387 €/lit
Scenario 1 Units	1
Scenario 2 Units	1

Table 3.8: Technical specifications and Costs of VOLVO PENTA TAD1345GE.

Parameters (Units)	Value
Model	VOLVO PENTA TAD1345GE
Rated power (kW)	250 kW
Lifetime	15000 h
Minimum Load Ratio (%)	40%
Specific fuel consumption (100% load)	283.63 lit/MWh
Capital Cost (€)	0 €
Replacement Cost (€)	38000 €
Operating and Maintenance Cost (€/hour)	0.15 €/hour
Diesel Cost	1.387 €/lit
Scenario 1 Units	2
Scenario 2 Units	1

Table 3.9: Technical specifications and Costs of MAN D2566ME.

Parameters (Units)	Value
Model	MAN D2566ME
Rated power (kW)	80 kW
Lifetime	10000 h
Minimum Load Ratio (%)	56.25%
Specific fuel consumption (100% load)	270.1 lit/MWh
Capital Cost (€)	0 €
Replacement Cost (€)	6000 €
Operating and Maintenance Cost (€/hour)	0.06€/hour
Diesel Cost	1.387 €/lit
Scenario 1 Units	2
Scenario 2 Units	1

3.5.4 Batteries Modelling, Size and Cost

Another important part of the hybrid system is the energy storage. In the market there are various type of energy storage (like batteries, flywheels, air-compressors, hydro pumped-storage), a optimal choice for applications of low and medium voltage are the batteries due to their low capital cost and abundant efficiency. Batteries are able to provide, among many merits, a good quality of electrical power, a reliable power supply and reduce the fluctuations caused by wind and solar energy. The overall battery dimensions are directly linked with required period for supplying the load without recharging. As for the battery size another important factor is the battery allowable depth of discharge (DOD). Especially for low and medium voltage autonomous hybrid systems and microgrids, optimal type of batteries are Deep-Cycle batteries due to load patterns because consumption occurs at a steady rate and shifting from the hours of solar production. Lifetime and efficiency of this type of batteries are not directly linked with the continuous use of the battery. In power system applications 2 types of batteries are mostly used: the lead-acid and lithium-ion batteries. [41] Lead-acid batteries are used in hybrid energy systems and microgrids widely worldwide. Their advantages are

the low initial investment cost, reliability over other energy storage technologies and their high effectiveness. [42] Battery bank is considered to be a set of one or more individual batteries. In this study, the simulated battery system is assumed as a single battery modelled as a device which can store a certain amount of DC electricity at fixed round-trip energy efficiency. Furthermore, it has limits concerning how quickly it can be charged or discharged, how deeply it can be discharged without causing damage, and how much energy can cycle through it before it needs to be replaced. Charging and discharging capacities can be seen in the formulas below. [43]
Battery charging:

$$P(t) = P_b \times (t-1) \times (1-\sigma) + [P_{bh}(t) - \frac{P_{bl}(t)}{\eta_{bi}}] \times \eta_{bb} \tag{3.15}$$

Battery discharging:

$$P_b(t) = P_b \times (t-1) \times (1-\sigma) - [\frac{P_{bh}(t)}{\eta_{bi}} - P_{bl}(t)] \tag{3.16}$$

where:
P_b is the battery energy in time interval,
P_{bh} is the total energy generated by PV array,
P_{bl} is the load demand in time interval,
η_{bi} is the inverter efficiency,
η_{bb} is the battery charging efficiency,
σ is the self discharging factor.

In this study after studying different studies for off-grid hybrid systems and microgrids, lead-acid batteries are chosen. The model which is input through the HOMER tool library is the Hoppecke 24 OPzS 3000 from the manufacturer Hoppecke which is a lead-acid, deep-cycle type battery. Nominal capacity of this battery is 3570 Ah (7.15 kWh) with a nominal voltage of 2 Volt. After surveying the market of batteries for the specific model, initial capital cost varies from 890 €- 1530 €. Thus initial capital cost is considered at 1200 €, in addition, replacement cost for battery is assumed about 80% of its capital cost 840 €, operation and maintenance, finally, are considered to be 12 €/year. In Table 4.10 can be seen the battery characteristics given by the manufacturer and the costs of the battery.

In addition, in order to be determined the optimal number of units for each scenario, a rough approximation is performed based on the following methodology. According to the following formula is calculated the total required capacity of the battery bank (Ah). [7]

$$C_{tot,cap} = \frac{n_{day} \times E_L}{\eta_{bat} \times DOD \times V_{bat}} \tag{3.17}$$

where:
$C_{tot,cap}$ is the total required capacity of the battery bank (Ah),
n_{day} is the number of days for which it is considered the battery storage bank can offer autonomy to the system,

Table 3.10: Technical specifications and costs of Hoppecke 24 OPzS 3000 battery.

Parameters (Units)	Value
Nominal Voltage (V)	2 V
Nominal Capacity (kWh)	7.15 kWh
Maximum Capacity (Ah)	3570 Ah
Round efficiency (%)	86%
Minimum State of Charge (%)	30%
Maximum Charge Current (A)	610 A
Lifetime (years)	20 years
Capital Cost (€)	1200 €
Replacement Cost (€)	840 €
Operating and Maintenance Cost (€/year)	12 €/year

E_L is the average daily energy consumption in (kWh),
η_{bat} is the overall battery and inverter efficiency,
DOD is the Depth of Discharge of the battery (%),
V_{bat} is the battery nominal voltage (2 Volt).
E_L is 3460.3 kWh for this study. Overall battery and inverter efficiency is calculated at 0.82, Depth of Discharge of the battery (DOD) is 0.7 and the number of autonomy days of the battery is selected for Scenario 2 (Wind - PV - Diesel - Battery) (Section 4.6) n_{day} = 1 and for Scenario 3 (Wind-PV-Battery) ((Section 4.6) n_{day} = 5 and n_{day} = 3. So $C_{tot,cap}$ for Scenario 2 is calculated at 3014.2 Ah and for Scenario 3 at 15071 Ah and 9042.6 Ah respectively. After that the total number of batteries is calculated using the equation 4.18.

$$n_{batteries} = \frac{C_{tot,cap}}{C_{single}} \tag{3.18}$$

where:
$n_{batteries}$ is the number of the required batteries,
C_{single} is the capacity of a single battery (7.15 kWh) for this study. As a result of the above the number of batteries for Scenario 2 is estimated at 422 batteries and for Scenario 3 at 2108 and 1264 batteries. The DC bus voltage is considered at 24 Volt. The nominal system voltage of the DC bus (48 Volt) should be equal to the summation of the voltages provided by each string of batteries. The number of string is calculated according to the next formula. The voltage of a single bus as mentioned earlier is 2 Volt so each string is going to contain 12 batteries $(12 \times 2V = 24)$

$$n_{string} = \frac{n_{batteries}}{V_{DCbus}/V_{bat}} \tag{3.19}$$

where: n_{string} is the number of strings of the battery,
$n_{batteries}$ is the number of the required batteries,
V_{DCbus} is the DC bus voltage,
V_{bat} is the battery nominal voltage (2 Volt).
According to formula 4.19, for Scenario 1 number of strings is equal to 35.16 but is not

an integer so the calculated number of batteries is going to be 420 instead of the primary calculation of 422 with 35 strings. In addition, for Scenario 3, as for case with autonomy days, n_{day} = 5 the calculated number of batteries was 2108 and number of strings according to formula 4.19 is 175.66 so the calculated number of batteries changes from 2108 to 2112 and respectively number of strings from 175.66 to 176. For the sub-case of Scenario 3 with autonomy days, n_{day} = 3, number of batteries was 1264. Using equation 4.19 number of strings is calculated at 105.33 so it is rounded at 105 string and number of batteries decreases at 1260.

3.5.5 Converter Size and Cost

A converter is an essential part of the hybrid system in order to maintain the balance of energy between AC and DC. A converter can operate as both an inverter and a rectifier. In this study the efficiency of the inverter is set at 90% and the efficiency of the rectifier at 85%. Lifetime is set at 15 years. The initial capital cost of converter according to [5] is 250 €/kW and operational and maintenance cost is 230 €/kW. Converter sizes that are considered in this study are: for Scenario 1: 80, 90, 100 and 200 kW. As for Scenario 2 the Search Space is : 100, 200, 300, 400 and 500 kW. Finally, for Scenario 3 Case 1 search space is: 400, 410, 420, 430, 440, 450, 460, 470, 480, 490 and 500 kW and for Case 2: 200, 250, 300, 350, 400, 450, 500, 550 and 600 kW.

3.6 Other Inputs that Affect Power System Optimization

3.6.1 Constraint inputs

Constraint tab in HOMER software is a set of limitations defined by the power system designer to make the hybrid system feasible and operational. Shortage capacity is considered to be a shortfall created by the required operating capacity and the actual amount of operating capacity the system can provide during a specific time period. Moreover, the operating capacity consists of the surplus demand and operating reserve loads. Operating reserve is a safety margin in case of excess electrical energy generating capability which ensures the smooth supply of electricity despite of the load, solar and wind imbalances. Excess electricity is created by the intermittent nature of RES (renewable energy sources) when generate surplus energy which is above load demand in combination with the inability of the battery to store excess energy because is fully-charged. For this study the maximum annual capacity shortage is set at 0%, the minimum renewable fraction is set at 40%, operating reserve is set as percentage of hourly load 10% and annual peak load of 0% and as a renewable fraction solar power output is set at 25% and wind power output at 100%.

3.6.2 Economic inputs

HOMER software, as it mentioned earlier make simulations according to the optimal NPC (Net Present Cost). NPC is depended of the parameters of the Economics tab window in HOMER software. Economic input parameters include like project lifetime, annual real interest rate, capacity shortage penalty, system fixed capital cost, system fixed O&M cost and currency. System fixed capital cost, system fixed O&M cost and capacity shortage penalty are set to zero value due to the fact that have no effect on the system rankings.

A very important variable for the simulation and the optimization of the system is Real Discount Rate. HOMER calculates the annual real discount rate (also called the real interest rate or interest rate) from the nominal discount rate and expected inflation rate inputs. Annual real discount is given by the formula below.

$$i = \frac{i' - f}{1 + f} \tag{3.20}$$

where:
i is the real discount rate,
i' is the nominal discount rate (the rate at which you could borrow money),
f is the expected inflation rate.
The real discount rate according to the Bank of Greece is 4.25%, the inflation rate this time in Greece is 0% so the expected real discount rate calculated from formula 4.1 is 4.25% and it is used for the calculation of the NPC cost. In addition, project lifetime is set at 25 years and all the costs are measured in the currency of Euro.

3.6.2.1 Net Present Cost (NPC)

As mentioned earlier HOMER software calculates NPC (Net Present Cost) of each proposed power system. So software ranks the power systems it proposes in descending order based on NPC. The total net present cost (NPC) of a system is the present value of all costs of the system during its life minus revenues and present value of the system. It is an important indicator as indicates if the whole investment is profitable or not. The NPC is given by the formula below. [44]

$$NPC = \frac{C_{ann,tot}}{CRF(i, Rproj)} \tag{3.21}$$

where:
$C_{ann,tot}$ is the total annualized cost ($/year),
CRF is the capital recovery factor (calculated in formula 4.3 below),
i is the real discount rate,
R_{proj} is the project lifetime.
The capital recovery factor (CRF) is a formula which is used for the calculation of the present value of an annuity. The equation of CRF can be seen below.

$$CRF(i, N) = \frac{i \times (1 + i)^N}{(1 + i)^N - 1} \tag{3.22}$$

where:
N is the number of years,
i is the real discount rate.

3.6.2.2 Levelized Cost of Energy (LCoE)

Levelized cost of energy is defined by HOMER (LCoE or COE) as the average (cost/kWh) of useful electrical energy produced by the system. THe software calculates LCoE from the following equation.

$$COE = \frac{C_{ann,tot} - c_{boiler} \times H_{served}}{E_{served}} \tag{3.23}$$

where:
$C_{ann,tot}$ is the total annualized cost ($/year),
c_{boiler} is the boiler marginal cost ($/kWh),
H_{served} is total thermal load served (kWh/year),
E_{served} is the total electrical load served (kWh/year).
E_{served} is equal with the sum of $E_{pr,AC}$ (AC primary load served (kWh/year)), $E_{pr,DC}$ (DC primary load served (kWh/year)) and $E_{gr,sales}$ (total grid sales (kWh/year)). This study does not consider any sale of energy to the grid. [45]

3.6.3 Emission Parameters

Greece has adopted European Union policies and measures to 2020 and one policy and measure is about the reduction of GHG (Greenhouse gas) emissions by 20% from the 1990 level by 2020. [1] In HOMER software another important tab is the Emissions tab window. In this window there are some values, Carbon dioxide, Carbon monoxide, Unburned hydrocarbons, Particulate matter, Sulfur dioxide, Nitrogen oxides. According to HEDNO S.A. (Hellenic Electricity Distribution Network Operator S.A.) the power system of Donoussa island is of a small scale so there are no purchase cost of emission rights of CO_2. As a result of this there are no penalties and the values of the Emissions window in HOMER software are set to 0.

3.6.4 Dispatch Strategy

A dispatch strategy is considered to be very simple when a system consists only PV, wind turbines and batteries. On the other hand it becomes complex when generators are added to the hybrid system. A dispatch strategy is defined as a control algorithm which switches battery bank and generators if there is insufficient renewable supply to meet the load demand. Different operational strategies can be used for the optimisation of the hybrid system and each strategy has its own merits and drawbacks. HOMER software has the capability of simulating and optimizing model with various controllers and gives the results which are suitable for comparisons. In this study the main dispatch strategies ”Load Following” (LF) and ”Cycle Charging” (CC) were selected for the scenarios. In ”Load Following” strategy, diesel generators operate and produce only enough power to meet the load demand when RES (renewable energy sources) are insufficient. RES (renewable energy sources) are responsible for the charging of the batteries and storage in generally and for the serving of the deferrable load. On the other hand, in the ”Cycle Charging” strategy diesel generators operate at full output power in order to serve the primary load. Once the load has served, surplus electrical production is used to serve the deferrable load, charge the batteries and provide the optimal amount of energy to electrolyzer for hydrogen production. During this strategy batteries are charged to the set-point state of charge (SOC) with no interruption. Start cycles of generators are reduced as well as charge and discharge cycles of the battery and the waiting time of the battery at minimum state of charge. In this thesis, whenever Cycle Charging (CC) is used the set-point state of charge (SOC) is set at 80%. Both dispatch strategies were involved in the simulations and the optimal strategy was selected for each scenario. [25]

3.7 Excess Electricity

Excess Electricity is surplus energy that is produced in a hybrid system. This energy cannot meet the load demands or charge the batteries so it has to be dumped or curtailed. It is usually produced by the intermittent nature of RES when battery is not able to store the Excess Electricity because is fully charged or by a generator when its minimum output exceeds the load. Excess Electricity is an important parameter for the voltage and frequency stability of the system and have to be zero in order the system to operate stable and supply the electricity reliably to consumers. Excess power can be usable in many ways. Desalination systems like Reverse Osmosis especially in islands can use the excess power for their operation. Besides, Excess Electricity can be reused for the cooling and the heating for households. The surplus energy that the system is not able to use, might be dissipated in a dump load which is usually a simple resistive heater or a bank of light bulbs. [40]

3.8 Sensitivity Variables

HOMER software gives the user the opportunity to take account dynamic changes like increasing or decreasing inputs, demands and renewable and non-renewable resources fluctuations. Sensitivity variables and parameters are used in order to show the user how sensitive the hybrid system/mircogrid is for the different values of the input variable. The main merit of the sensitivity analysis is the study the uncertainty, the changes of the system and how the sizes of the components are affected and the right ranges of components to be selected. The computational time of HOMER software increases as the number of the sensitivity variables increases which is a challenge for the software. Computational time is directly linked with the sizes of the power system components and as mentioned earlier with the quantity of sensitivity parameters. The accuracy of the optimization results increase when there is a large number of sensitivity variables. On the other hand the computational time is long and the memory of the computer needs to be larger. The sensitivity variables that are taken into consideration for this study are depicted in the Table 3.11 along with the corresponding scenarios. For Scenario 1 a decrease of 20% and an increase of 20% in diesel price (1.387 €) is considered, so the sensitivity values of Diesel Price are 1.110, 1.387 and 1.664 €. As for Scenario 2 variations on diesel price similar to Scenario 1 and variation on wind speed of 20 % are included in order the impact of these variations to the hybrid system to be examined. Finally, as for Scenario 3 an increase of 20% in solar irradiation data and in wind speed is going to be applied. Table 3.11 depicts different sensitivity variables for the different scenarios. [40]

Table 3.11: Sensitivity analysis variables

<table>
<tr><th>Scenarios</th><th colspan="2">Sensitivity Variables</th></tr>
<tr><td rowspan="2">Scenario 1</td><td colspan="2">Diesel Price</td></tr>
<tr><td colspan="2">1.110 €, 1.387 €, 1.664 €</td></tr>
<tr><td rowspan="2">Scenario 2</td><td>Diesel Price (€)</td><td>Average Wind speed (m/s)</td></tr>
<tr><td>1.11 € , 1.387 € , 1.664 €</td><td>5.68 m/s, 7.10 m/s, 8.52 m/s</td></tr>
<tr><td rowspan="2">Scenario 3</td><td>Annual Average Solar Radiation (kWh/m²/day)</td><td>Average Wind speed (m/s)</td></tr>
<tr><td>4.34, 5.42, 6.50 kWh/m²/day</td><td>7.10 m/s, 8.52 m/s</td></tr>
</table>

Chapter 4

Results and Discussion

In this chapter are going to be discussed the optimization results for each scenario as well as the sensitivity analysis results. The assessment is going to cover both the technical and economical system performance for 20 years lifetime. Firstly optimization results are going to be presented and then the sensitivity results and how they affect the hybrid system. Optimization results are going to be studied in respect with the lowest Excess Electricity Energy which is a factor that can cause a lot stability problems and is the main parameter to select the optimal system for each scenario. Then the optimal hybrid system is going to be selected with respect to the NPC (Net Present Cost) and LCoE (Levelized Cost of Energy). Sensitivity analysis variable fed into HOMER software to determine optimal system according to different condition that were mentioned earlier in Section 3.7. Furthermore, Hybrid system Scenarios that are examined, were described in section 3.4. Simulations have been performed with inputs parameters and system constraints that were described in Chapter 3. During these simulations, HOMER software objectively classified each hybrid system combination according to the net present cost, operating cost per year, initial capital, cost of electricity, renewable fraction, and gasoline consumption. Then the combinations which had the lowest NPC (Net Present Cost) and LCoE (Levelized Cost of Energy) are selected as optimal solutions.

4.1 Optimization Results

4.1.1 Scenario 1/Diesel-PV-Wind Hybrid system

The optimization results can be seen in the Table 4.1 for Scenario 1 which consists of PV panels, 5 Diesel generator units, Wind turbines and RF (Renewable Fraction) of 20%. The most optimal Hybrid Renewable Energy Systems (HRES) to meet the load demands of Donoussa island for this scenario consists of: 70 kW PV, 2 Eocycle Wind Turbines (20 kW each turbine), 5 operating conventional units (diesel generators) and 1 converter of 80 kW. The Excess Electricity percentage is very low at 6.68% and the RES (Renewable Energy Sources) participate in the production as a percentage 20.2% over the RF (Renewable Fraction) limit. Excess Electricity is at a very low value (90,807 kWh/yr) and this extra energy can be used for desalination technologies like Reverse Osmosis. The dispatch strategy that is used is Cycle Charging, with NPC (Net Present Cost) at 4,950,408 € and LCoE (Levelized Cost of Energy) at 0.2948 €. The total power production of this power system setup is 1,359,120 kWh/year, whereas the total electric power consumption of the AC load is about 1,263,010 kWh/year. The analytical production of each component can be seen in the Table 4.2 as well as the technical characteristics.

Table 4.1: Scenario 1 Optimization results.

Systems	PV (kW)	EO20 (WT)	TAD 740GE (kW)	TAD 1345GE (kW)	TAD 1345GE (kW)	D2566 ME (kW)	D2566 ME (kW)	Conv (kW)	Excess Elec (%)	NPC (Millions €)	COE (€)	Ren Frac (%)	Dispatch
System 1	100	2	200	250	250	80	80	80	6.68	4.95	0.295	20.2	CC
System 2	100	2	200	250	-	80	80	80	6.68	4.97	0.296	20.2	CC
System 3	100	2	200	-	250	80	80	80	3.17	4.97	0.296	20.2	CC

Some useful remarks regarding Scenario 1 can be derived from Table 4.2. At first the load demands on the island are satisfied with 5 out of 6 diesel generators of the existing power systems. The main production to cover the needs of the island in this scenario comes from Diesel Generators which are already installed on the island. Conventional units produce nearly 74.18 % of the total production. The low operational hours of Diesel generators (TAD 1345GE 855 hrs/yr) suggest that the system could cope with less conventional units (Scenario 2). In this specific scenario PV panels and Wind turbines produce 20.2 % of the total production of electricity for the island load demands. The monthly electrical production of each component can be seen in Figure 4.1. PV panels and Wind Turbines produce energy at a constant rate during throughout the year. The diesel generator Volvo Penta TAD1345GE seem to operate a lot of hours during summer months when the load demands are high due to tourism.

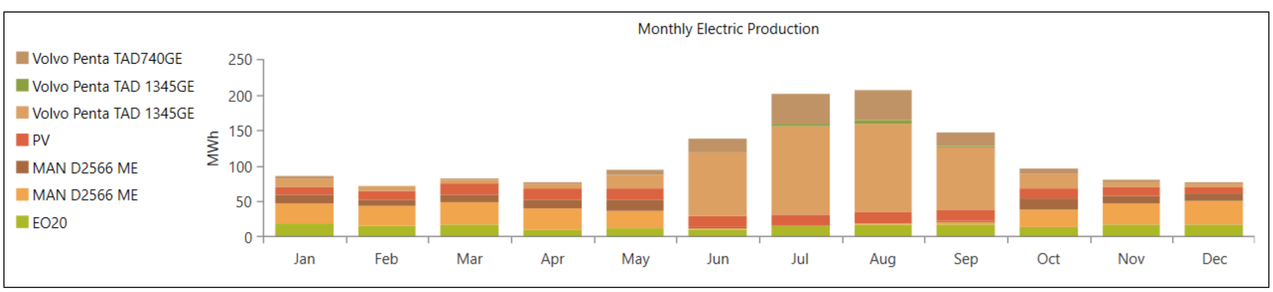

Figure 4.1: Monthly Electrical Production of Scenario 1.

Diesel generators VOLVO PENTA TAD740GE and two MAN D2566ME maximum power outputs occur during the months of January, February, April, May, October, November and December. Figures 4.2, 4.3 and 4.4 below show the Power Output of the VOLVO PENTA TAD1345GE diesel generator and the two MAN D2566ME.

Table 4.2: Analytical Electrical Production and technical characteristics for optimal configuration of Scenario 1.

System Components	Production (kWh/yr)	Production %	Mean Output (kW)	Annual fuel consumption L/yr	Operational hours hrs/yr
PV	164,853	12.1	18.8	-	4,386
TAD740GE	151,860	11.2	112	36,447	1,353
TAD 1345GE	509,656	37.5	150	119,781	3,396
TAD 1345GE	9,486	0.698	112	2,229	85
MAN D2566 ME	234,188	17.2	45	27,737	2,291
MAN D2566 ME	103,095	7.59	47.1	63,022	4,976
Eocycle EO20	185,982	13.7	21.2	-	7,708
Total	1,359,120	100	-	249,215	-

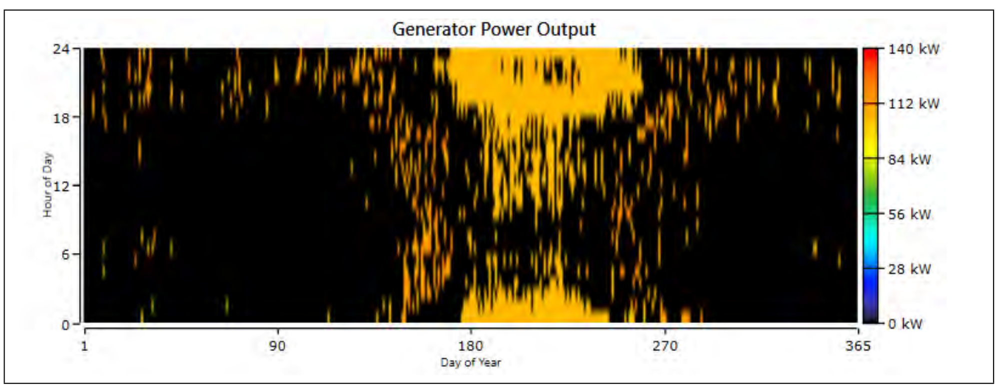

Figure 4.2: Power output of VOLVO PENTA TAD740GE.

The power output of two diesel generators of type VOLVO PENTA TAD 1345GE is depicted in Figure 4.5 and 4.6. It is observed that the usage of the second VOLVO PENTA TAD 1345GE is nearly zero and as a result of this its usage in a hybrid system like this is considered inadequate. In general it is clear that diesel generators maximum power output in all generators occurs during evening time and during the night when PV and Wind Turbines

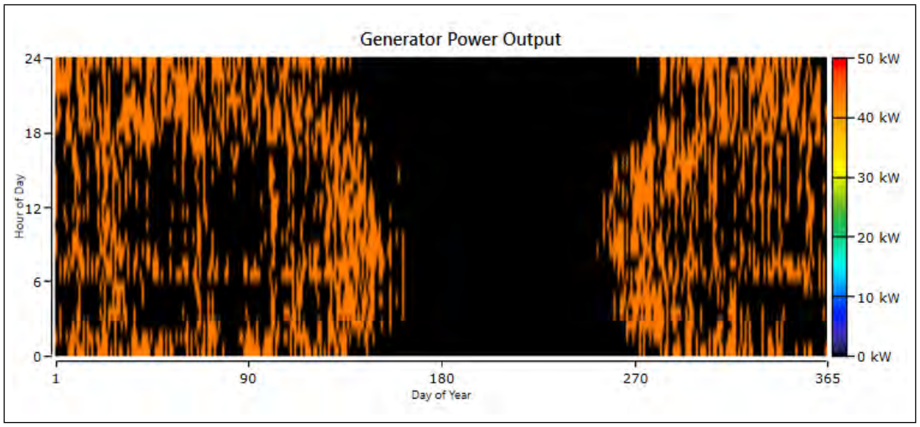

Figure 4.3: Power output of MAN D2566ME.

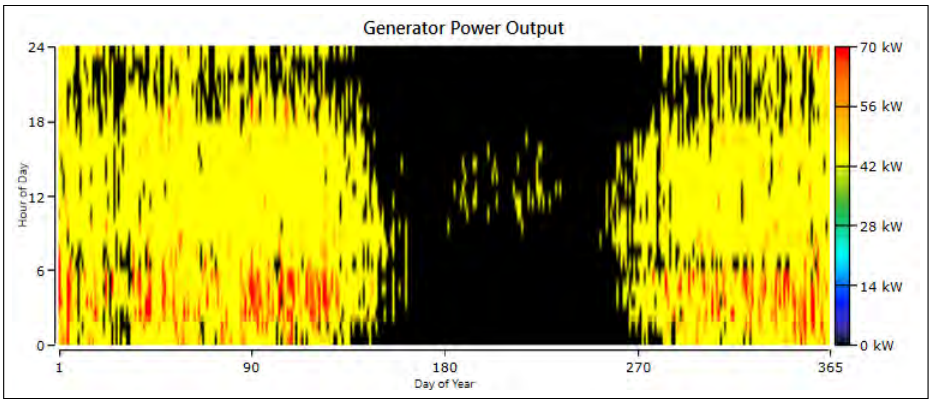

Figure 4.4: Power output of MAN D2566ME.

power output is low. Main drawback in the usage of conventional diesel generators on this type of HRES (Hybrid Renewable Energy Systems) is environmental pollution by fuel emissions. The total fuel consumed is 249,215 liter/year. Fuel summary is depicted in Figure 4.7 and it can be easily concluded the high consumption of fuels during the summer months until September when the usage of diesel generators is maximum. The usage of RES (Renewable Energy Sources) declines emission pollutants, Co2, Co, So2, Nox and particulate matters from emitting to the atmosphere. Table 4.3 shows the pollutant that are emitted in atmosphere for this scenario.

Table 4.3: Scenario 1 Emissions.

Quantity	Value (kgr/yr)
Carbon Dioxide	668,493
Carbon Monoxide	4,072
Unburned Hydrocarbons	179
Particulate Matter	24.4
Sulfur Dioxide	1,636
Nitrogen Oxides	3,828

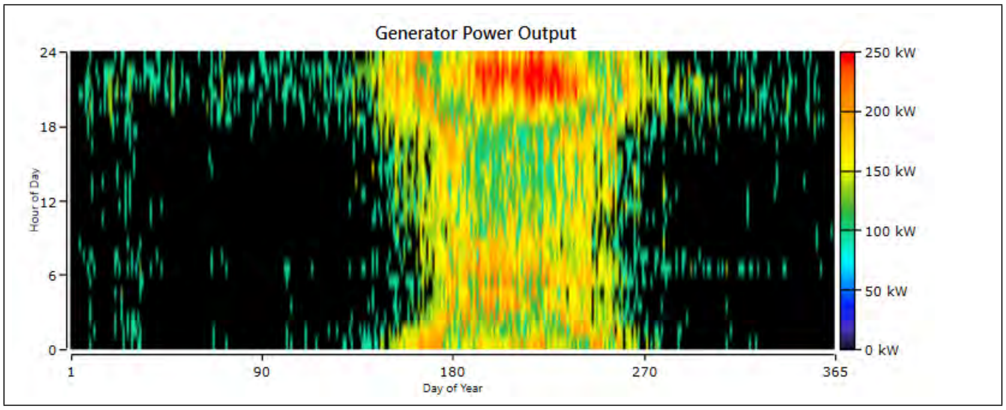

Figure 4.5: Power output of VOLVO PENTA TAD 1345GE.

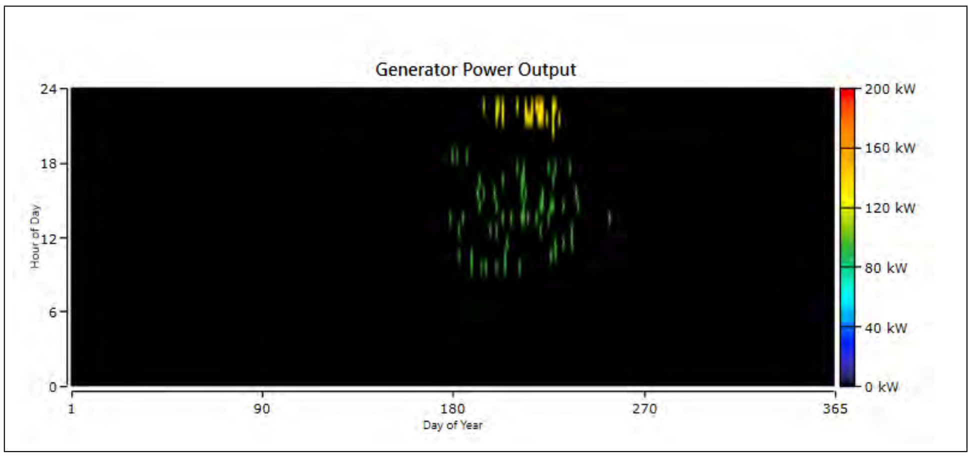

Figure 4.6: Power output of VOLVO PENTA TAD 1345GE.

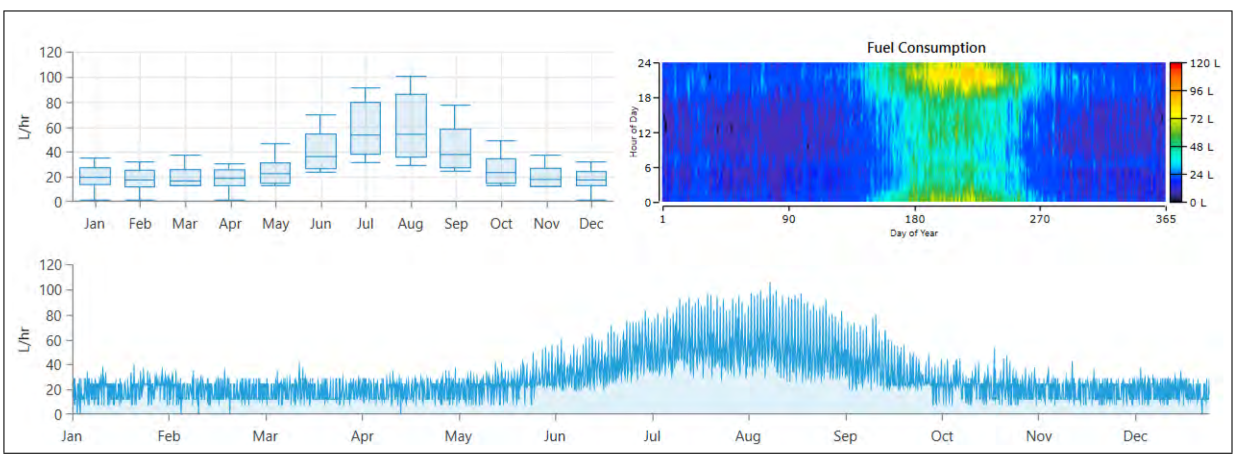

Figure 4.7: Fuel summary Scenario 1.

Figure 4.8, 4.9 and table 4.4, depict the share of electricity generation from solar PV. As noticed from the two figures electricity generation is maximized in January, February and

November and not the months with high solar radiation striking the earth's surface like summer (April to September). The maximum power output of PV panels happens in November when maximum amount of irradiation strikes the surface of the island. 100 kW is the rated capacity of PV panels on this scenario, with a mean power output of 18.8 kW and a maximum power output of 88.6 kW. Solar PV panels total hours of operation is 4,386 hrs/yr as a result of this can be easily deduced that PV panels work almost 12 hours per day. Moreover, LCoE (Levelized Cost of Energy) of PV panels is at 0.0343 €/kWh. Table 4.4 depicts the PV scheme simulation results.

Table 4.4: PV Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	100	kW
Minimum Output	0	kW
Maximum Output	88.6	kW
Mean Output	18.8	kW
Mean Output	452	kWh/d
Capacity Factor	18.8	%
Total Production	164,853	kWh/yr
PV Penetration	13.1	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0343	€/kWh

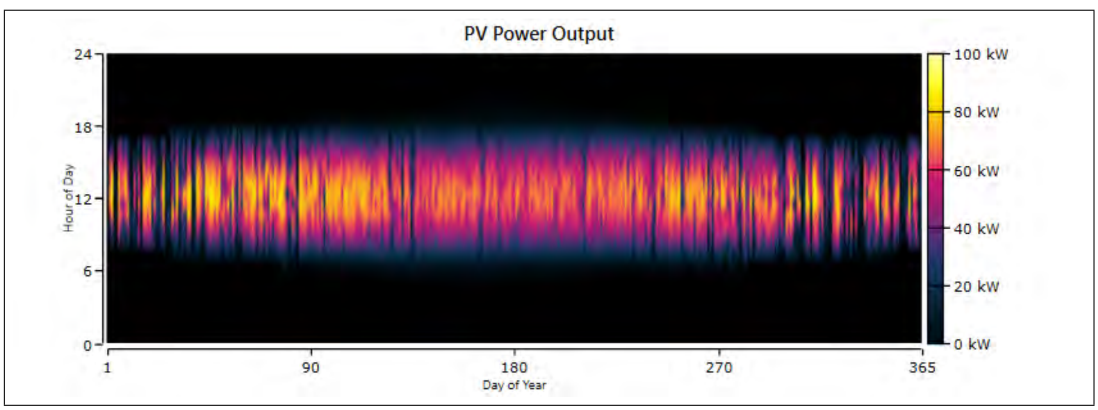

Figure 4.8: PV Power output.

As far as Wind Turbines are concerned, power output by the Wind Turbines is depicted in Figure 4.10. The power output is high during the year with a maximum of 40.6 kW in February. Mean output 21.2 kW confirms the fact that mentioned above, with a minimum power of 0 kW. Only April, May, June, July and October had an average Wind Turbine power output under the mean output of 21.2 kW. Furthermore, wind penetration is at a low percentage 14.7 % due to the 2 wind turbines are used in this scenario. LCoE of Wind Turbines is at 0.0405 €/kWh. Table 4.5 shows the Wind Turbines scheme simulation results.

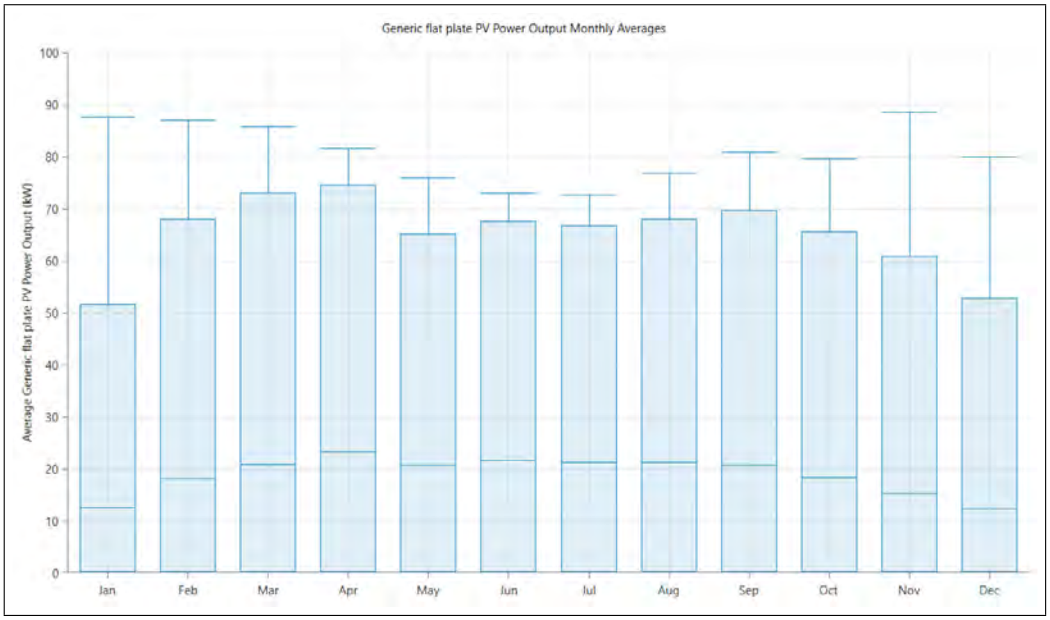

Figure 4.9: PV Power output monthly averages.

Table 4.5: Wind Turbines Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	20	kW
Minimum Output	0	kW
Maximum Output	40.6	kW
Mean Output	21.2	kW
Capacity Factor	53.1	%
Total Production	185,982	kWh/yr
Wind Penetration	14.7	%
Hours of Operation	7,708	hrs/yr
Levelized Cost	0.0405	€/kWh

As for costs of the system, the optimal configuration was selected according to the minimum NPC (Net Present Cost) cost and LCoE. The main economic aspects for the optimal system are presented in Table 4.6. The financial characteristics of Table 4.6 are presented also in Figure 4.11. It can be easily derived that the main cost of the selected configuration is the fuel costs with a value of 4,595,337.32 €. This can be justified from the fact that the Renewable Fraction for this configuration is 20.2 % that it means diesel generators operate in order to satisfy the load demands and the fuel consumption happens at very high rate. The Initial cost/ Capital cost is very low due to the fact that diesel generator units have been already installed in power system of Donoussa. Cash flow during the lifetime of the project is depicted in Figure 4.12. During the lifetime after fuel costs, replacement cost have a remarkable share along with Capital cost.

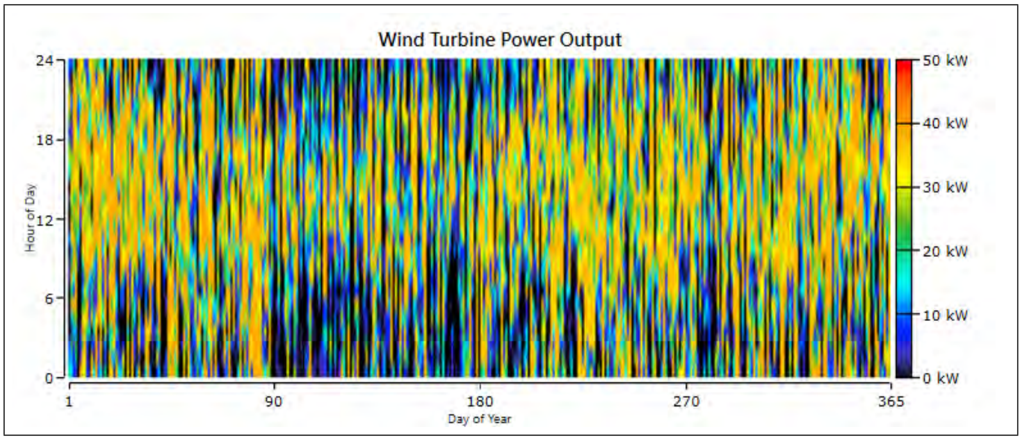

Figure 4.10: Wind Turbine Power output.

Table 4.6: Economic characteristics of the optimal configuration of Scenario 1.

System	NPC (€)	LCoE (€)	Capital (€)	Replacement (€)	Salvage (€)	O & M (€/yr)	Fuel (€)
Optimal	4,950,407.61	0.2948	153,600	175,581.04	-36,535.63	55,499.86	4,595,337.32

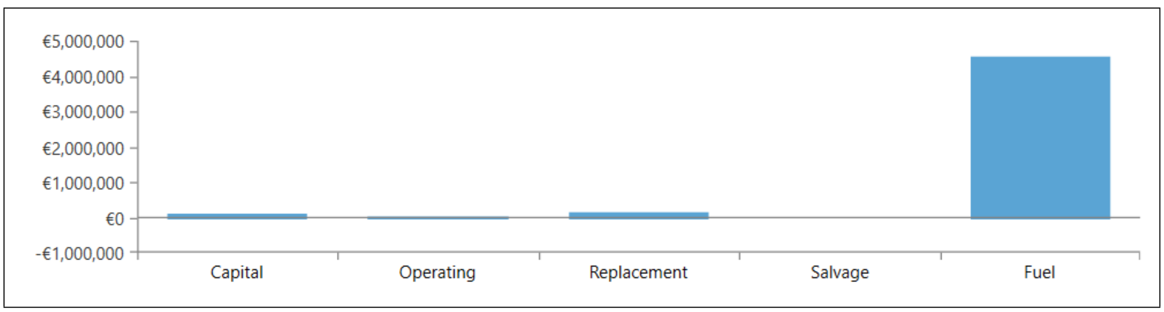

Figure 4.11: Cost summary by Cost type.

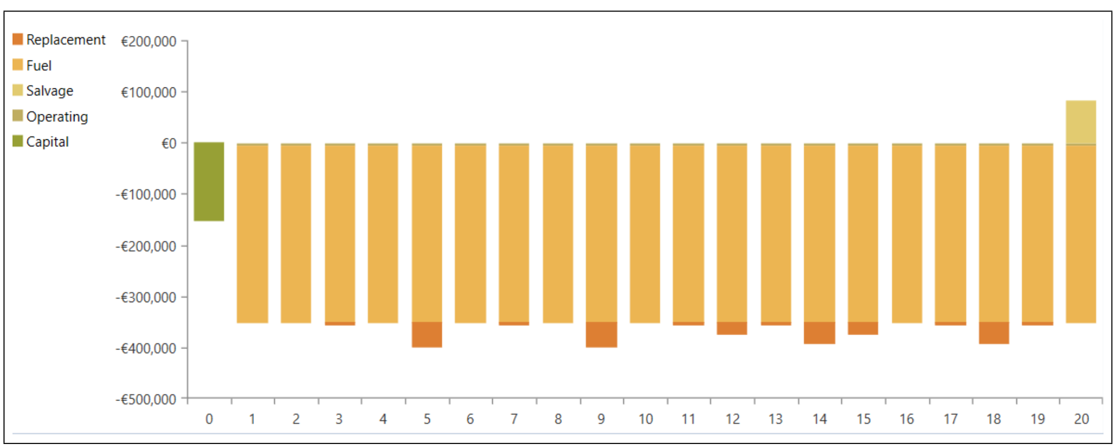

Figure 4.12: Cash flow by Cost type Scenario 1.

In addition, the details of the NPC by cost type for the optimal configuration is depicted in Figure 4.13. The main source of costs comes from diesel generators and more specifically from one of two VOLVO PENTA TAD1345GE with total cost of 2,846,274.84 €. Then other two diesel generators follow VOLVO PENTA TAD740GE and one of two MAN D2566ME with total cost 958,754.76 € and 576,481.42 € respectively. On the other hand the RES (Wind Turbines and PV panels) have a little share of the total NPC (Net Present Cost) of the hybrid system with 100,156.30 € and 75,218.24 € respectively. Analytical costs by each component are depicted in the Figure 4.14 and in Figure 4.15. Different colour represent the different cost of each component each year during lifetime of the project. Distribution with orange colour confirm the high costs of VOLVO PENTA TAD1345GE.

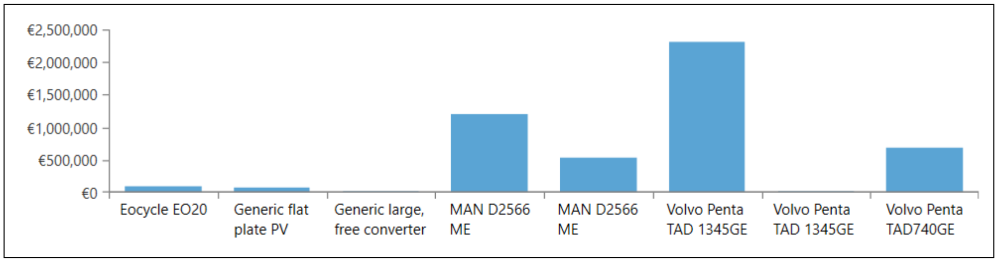

Figure 4.13: Cost summary by component type Scenario 1.

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Eocycle EO20	€71,600.00	€0.00	€28,556.30	€0.00	€0.00	€100,156.30
Generic flat plate PV	€62,000.00	€0.00	€18,612.11	€0.00	-€5,393.87	€75,218.24
Generic large, free converter	€20,000.00	€9,855.46	€0.00	€0.00	-€5,335.87	€24,519.59
MAN D2566 ME	€0.00	€36,378.24	€3,969.17	€1,162,073.04	-€125.28	€1,202,295.17
MAN D2566 ME	€0.00	€15,555.28	€1,827.44	€511,442.71	-€1,090.95	€527,734.48
Volvo Penta TAD 1345GE	€0.00	€98,032.64	€6,772.15	€2,208,667.27	-€7,801.97	€2,305,670.09
Volvo Penta TAD 1345GE	€0.00	€0.00	€169.50	€41,106.68	-€14,656.24	€26,619.94
Volvo Penta TAD740GE	€0.00	€15,759.42	€2,518.22	€672,047.62	-€2,131.45	€688,193.81
System	€153,600.00	€175,581.04	€62,424.89	€4,595,337.32	-€36,535.63	€4,950,407.61

Figure 4.14: Analytical costs of each component Scenario 1.

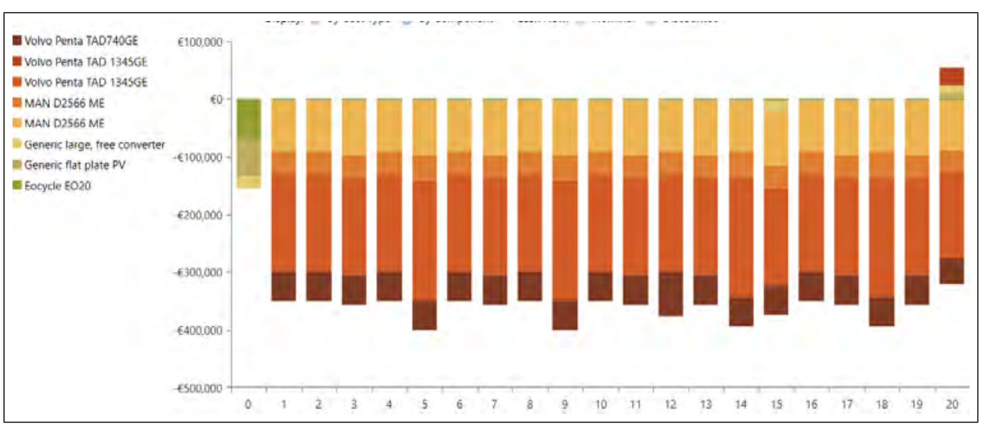

Figure 4.15: Cash flow by component type Scenario 1.

According to HEDNO (Hellenic Electricity Distribution Network Operator) for the year 2017 the power station of Donoussa island produced 1012.66 MWh. In addition, the average annual variable cost of conventional units of the Donoussa power system for the year 2017 taking into consideration fuel costs and additional operating and maintenance costs is equal to 250.02 €/MWh. The total cost of the year 2017 can be easily calculated at 253,185.25 € and if its is considered an average yearly cost, for lifetime of 20 years the total cost of the existing power system of Donoussa is 5,063,705.06 €. The total NPC (Net Present Cost) of Scenario 1 is 4,950,407.61 € which is a lower value from the cost for the existing power system by 113,297.45 €. This observation makes the optimal configuration of Scenario 1 feasible and viable for Donoussa island.

4.1.2 Scenario 2/Diesel-PV-Wind-Battery Hybrid system

In Scenario 2 the hybrid system is composed of Wind Turbines, PV panels, battery storage and diesel generators. Renewable fraction for this case is at 50% and feasible hybrid renewable energy systems (HRES) after the optimization is 2 as Table 4.7 depicts. Main target of this Scenario is the reduction of Excess Electricity as well as the NPC, the LCoE and the usage of conventional units. Both feasible systems have Excess Electricity at a 0% rate, first of them include MAN D2566ME while the other does not. There is a slight difference in the NPC, in the LCoE and in RF (Renewable Fraction) between the two configurations. Driven by these remarks it was decided to keep the first configuration of this scenario as the optimal system. Thus the optimal hybrid system consists of 260 kW of Panels, 2 Wind Turbines of type Eocycle EO20 (20 kW) , 2 Aeolos-H (10 kW) Wind Turbines, 1 unit of VOLVO PENTA TAD740GE diesel generator, 1 unit of VOLVO PENTA TAD1345GE diesel generator, 1 unit of MAN D2566ME diesel generator, 420 battery units and a converter of 200 kW. The optimal system configuration selected a load following dispatch strategy (LF) where the diesel generators only provided enough power to serve the load at any particular point in time and do not charge the batteries. The NPC is at 4,031,102 € and LCoE at 0.2401 € . Moreover, total power production of this power system setup is 1,307,797 kWh/year which is lower than the production of Scenario 1 (1,359,120 kWh/year) but is considered technical feasible and cover the load demands of Donoussa island with AC primary load consumption of 1,263,010 kWh/yr. Table 4.8 present the technical and electrical characteristics of the optimal system.

Regarding Table 4.8 some important remarks can be drawn concerning optimal configuration of Scenario 2. Comparing to Scenario 1 and with the existing power system of Donoussa island, the hybrid system include only 3 diesel generator units instead of 6 and 5 in Scenario 1 and in existing power system respectively. The production is divided almost equally between the conventional units and the RES with almost 47.28% of the total production comes from fossil fuels and almost 52.7% comes from PV panels and Wind Turbines. More specifically Wind Turbine contribute in the total production of almost 20% and PV panels 32.8%. The contribution of RES in total production is higher than Scenario 1 as the optimal system for Scenario 1 include 100 kW of PV panels and 2 Wind Turbines in contrast with the existing scenario with 260 kW of PV panels and 4 Wind Turbines. The low operational hours of diesel generator VOLVO PENTA TAD1345GE indicate that with a possible increase in RES the the hybrid system could meet the load demands with only 2 operational

Table 4.7: Scenario 2 Optimization results.

Systems	PV (kW)	EO20 (WT)	Aeolos-H	TAD 740GE (kW)	TAD 1345GE (kW)	D2566 ME (kW)	Battery	Conv (kW)	Excess Elec (%)	NPC (Millions €)	COE (€)	Ren Frac (%)	Dispatch
System 1	260	2	2	200	250	80	420	200	0	4.03	0.240	51.0	LF
System 2	260	2	2	200	250	-	420	200	0	4.11	0.245	50.1	LF

Table 4.8: Analytical Electrical Production and technical characteristics for optimal configuration of Scenario 2.

System Components	Production (kWh/yr)	Production %	Mean Output (kW)	Annual fuel consumption (L/yr)	Operational hours (hrs/yr)
PV	428,618	32.8	48.9	-	4,386
TAD740GE	429,150	32.8	136	109,093	3,153
TAD 1345GE	60,600	4.63	111	17,332	548
MAN D2566 ME	128,867	9.85	47.7	34,682	2,703
Eocycle EO20	185,982	14.2	21.2	-	7,708
Aeolos-H (10 kW)	74,579	5.70	8.51	-	7,374
Total	1,307,797	100	-	161,106	-

conventional units. Monthly electrical production of each component is presented in Figure 4.16. The production of VOLVO PENTA TAD740 diesel generator production is peaking in summer months due to the high load demands. During the year PV and Wind turbines produce electricity at a steady rate in higher rates compared to Scenario 1.

The greatest share in electrical production has the generator VOLVO PENTA TAD740GE

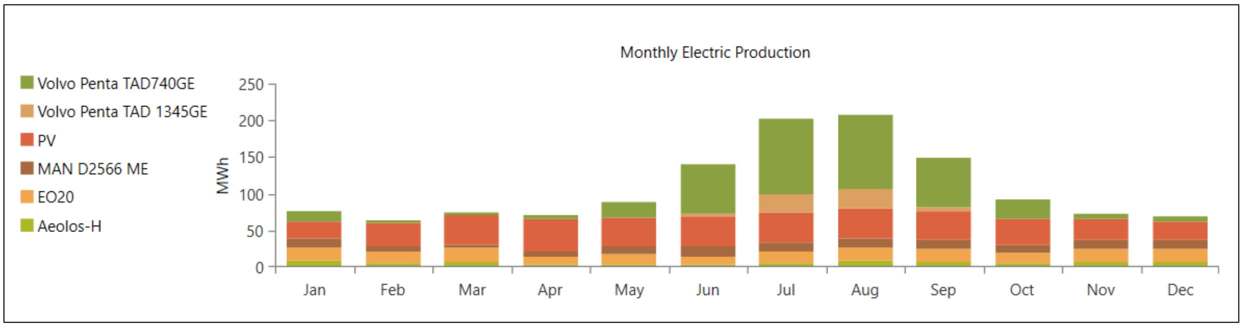

Figure 4.16: Monthly electrical production of each component of Scenario 2.

with 429,150 kWH/yr and 32 % in total production. The maximum power output of VOLVO PENTA TAD740GE occur during summer months and more specifically June, July and August due to tourism. On the other hand the power output is significantly reduced for the rest of the year. As it is observed in Figure 4.16, winter, spring and autumn months VOLVO PENTA TAD740GE operate mostly during the night and evening hours.

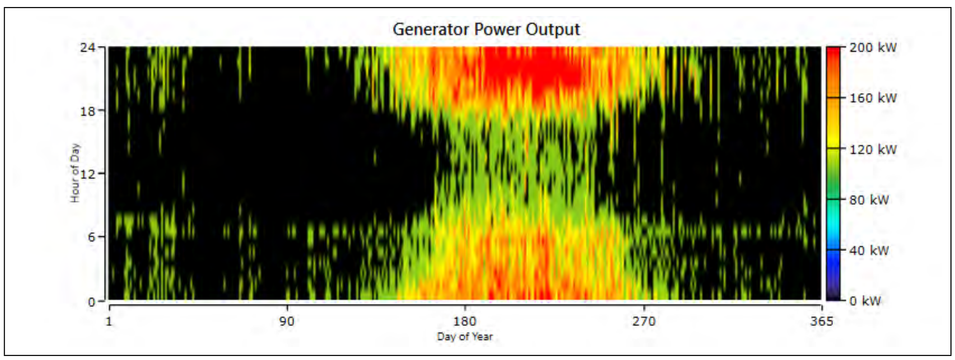

Figure 4.17: Power output of VOLVO PENTA TAD740GE.

As for the other two conventional units of the optimal configuration, as mentioned earlier VOLVO PENTA TAD1345GE operate few hours during the year with a mean electrical output of 111 kW and fuel consumption 17,332 liters. Operates only during summer months with a zero operation the rest months. MAN D2566ME with mean output at 47.7 kW operates 2,703 hours/yr with a stable rate and a peak of 80 kW on July and August. Figure 4.18, 4.19 present power outputs of VOLVO PENTA TAD1345GE and MAN D2566ME. In addition, total fuel consumed is 161,106 liter/year which is considered a much lower value than fuel consumption in Scenario 1 (249,215 liter/year) due to the reduction of conventional units. Fuel summary can be seen in Figure 4.20 below where the operation of conventional units during the summer months is directly linked with the peak fuel consumption during the summer. Pollutants are significantly reduced compared to Scenario 1 and are presented in Table 4.9.

Solar PV panels have a great share in the total electrical production of this Scenario with 32.8%. PV have a rated capacity in the optimal system configuration of 260 kW, mean output of 48.9 kW and 4,386 hours of operation. Furthermore, Donoussa is an island with great solar irradiation and PV panels produce power throughout the year. There is a clear increase on the rated capacity of PV panels 260 kW to 100 kW compared to Scenario 1 due to the increase

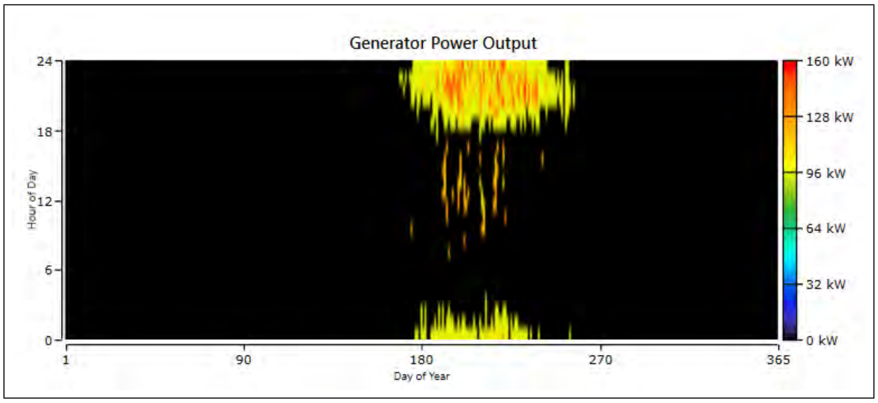

Figure 4.18: Power output of VOLVO PENTA TAD1345GE.

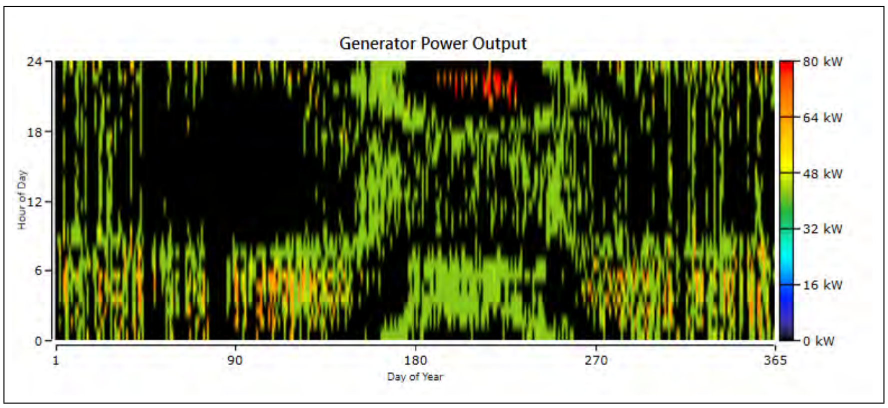

Figure 4.19: Power output of MAN D2566ME.

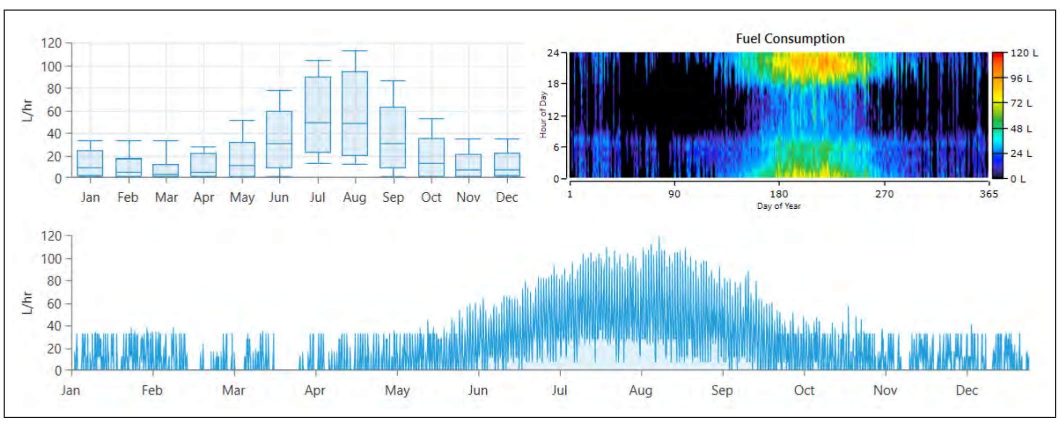

Figure 4.20: Fuel summary Scenario 2.

in the Renewable Fraction from 20% to 50%. In Table 4.10 and in Figure 4.21 below can be observed PV scheme simulation results.

Table 4.9: Scenario 2 Emissions.

Quantity	Value (kgr/yr)
Carbon Dioxide	432,152
Carbon Monoxide	2,632
Unburned Hydrocarbons	116
Particulate Matter	15.8
Sulfur Dioxide	1,058
Nitrogen Oxides	2,474

Table 4.10: PV Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	260	kW
Minimum Output	0	kW
Maximum Output	230	kW
Mean Output	48.9	kW
Mean Output	1,174	kWh/d
Capacity Factor	18.8	%
Total Production	428,618	kWh/yr
PV Penetration	33.9	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0343	€/kWh

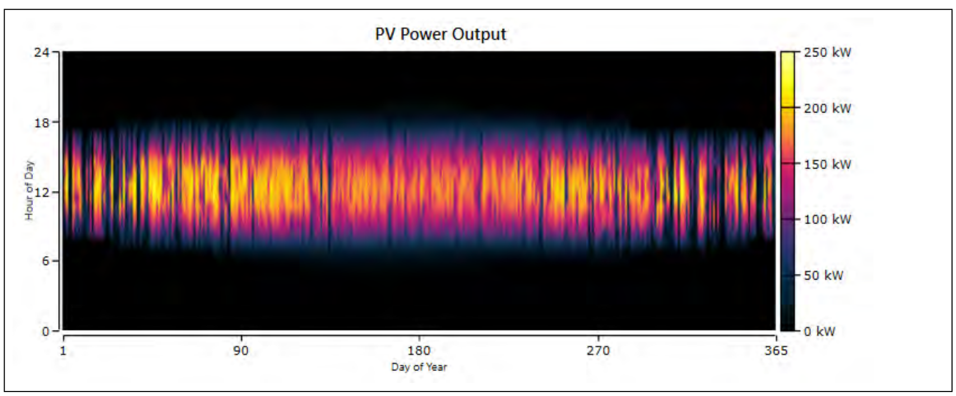

Figure 4.21: PV power output Scenario 2.

As far as Wind Turbines are concened, the optimal configuration hybrid system includes 4 Wind Turbines, a combination of 2 Eocycle EO20 (20 kW) and 2 of Aeolos-H (10 kW) with a total sum of 60 kW. In this scenario wind energy contributes in electrical production with almost 20% in total electrical production. It comes no surprise this fact because Greek islands and especially Donoussa is ideal for wind energy operation as it mentioned earlier in Chapter 3. Both models of Wind Turbines operate almost during all time of the year. Eocycle EO20 (20 kW) has an average operation under the mean output 21.2 kW only in April, May, June and October. Additionally, Aeolos-H operate under the mean output of 8.51 kW in April, May, June and July. Wind Turbine scheme simulation results and power output are depicted in Table 4.11, 4.12 and in Figures 4.22, 4.23. Figure 4.22 and 4.23 highlights the high reliance on wind energy where as it mentioned earlier Wind Turbines operate almost all year round.

Table 4.11: Eocycle EO20 (20 kW) Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	40	kW
Minimum Output	0	kW
Maximum Output	40.6	kW
Mean Output	21.2	kW
Capacity Factor	53.1	%
Total Production	185,982	kWh/yr
Wind Penetration	14.7	%
Hours of Operation	7,708	hrs/yr
Levelized Cost	0.0405	€/kWh

Table 4.12: Aeolos-H (10 kW) Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	20	kW
Minimum Output	0	kW
Maximum Output	27.6	kW
Mean Output	8.51	kW
Capacity Factor	42.6	%
Total Production	74,579	kWh/yr
Wind Penetration	5.9	%
Hours of Operation	7,374	hrs/yr
Levelized Cost	0.0506	€/kWh

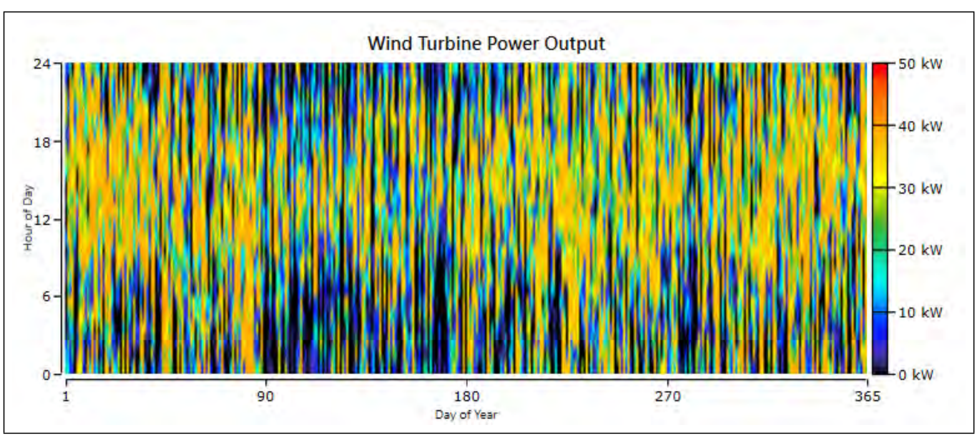

Figure 4.22: Eocycle EO20 (20 kW) power output Scenario 2.

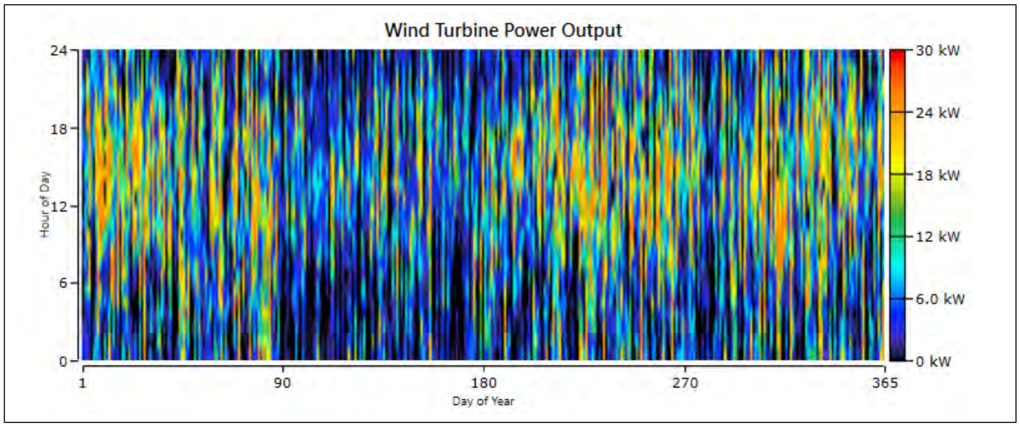

Figure 4.23: Aeolos-H (10 kW) power output Scenario 2.

In this scenario there is an extra important parameter for the hybrid system which is the energy storage. Batteries were solely being charged by the RES in this case (Solar PV panels, Wind Turbines) following Load Following dispatch strategy. Excess electricity from RES is absorbed for the charging of batteries. From Figure 4.24 below can be easily derived the fact that battery is at low levels of charge during spring and summer months due to the fact that during summer months energy needs are greater and battery has to contribute to energy production to meet the load demands. Battery is at high levels of charge during January, February, March, November and December due to the high operation of RES. Battery scheme simulation results are presented in Table 4.13.

Table 4.13: Battery Scheme Simulation Results.

Quantity	Value	Units
Batteries	420	qty
String Size	12.0	batteries
Strings in Parallel	35.0	strings
Bus Voltage	24.0	V
Autonomy	14.6	hr
Storage Wear Cost	0.0895	€/kWh
Nominal Capacity	3,003	kWh
Usable Nominal Capacity	2,102	kWh
Energy In	162,376	kWh/yr
Energy Out	141,538	kWh/yr
Storage Depletion	2,043	kWh/yr
Losses	22,881	kWh/yr
Annual Throughput	152,625	kWh/yr

The optimal system configuration NPC (Net Present Cost) is at 4,031,102.03 € and LCoE is 0.2401 €. There is a sufficient difference between NPC of Scenario 1 and Scenario 2, 4,950,407.61 € to 4,031,102.03 € and in LCoE 0.2948 € to 0.2401 €. Table 4.14 summarizes the financial aspects of the optimal configuration of Scenario 2. The cost summary by cost type is presented in Figure 4.25. It can be easily derived like Scenario 1 that the main

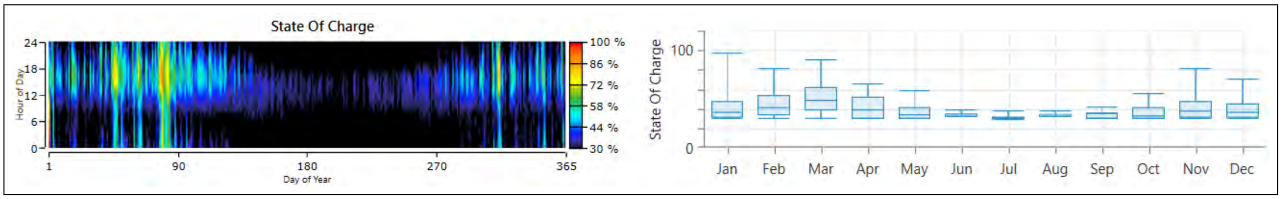

Figure 4.24: Battery State-of-Charge Scenario 2.

core of costs are fuel costs with 2,970,686,19 € and are less than Scenario 1 (4,595,337.32) due to the existence of fewer diesel generators (5 in Scenario 1 and 3 in Scenario 2) and the great share of RES in Scenario 2 (RF = 50.1%). As a result of this fuel consumption is decreased and fuel costs are almost in the half price of fuel costs of Scenario 1. Capital costs are 822,600.00 € and have the second greatest share in total costs of the hybrid system. Capital costs are justified from the purchase, installation and transportation of RES (PV panels and Wind Turbines), which have larger rated capacity than RES that are included in Scenario 1. Cash flow during the lifetime of the project is presented in Figure 4.26.

Table 4.14: Economic characteristics of the optimal configuration of Scenario 2.

System	NPC (€)	LCoE (€)	Capital (€)	Replacement (€)	Salvage (€)	O & M (€/yr)	Fuel (€)
Optimal	4,031,102	0.2401	822,600	112,901.73	-42,539.07	167,453.17	2,970,686.19

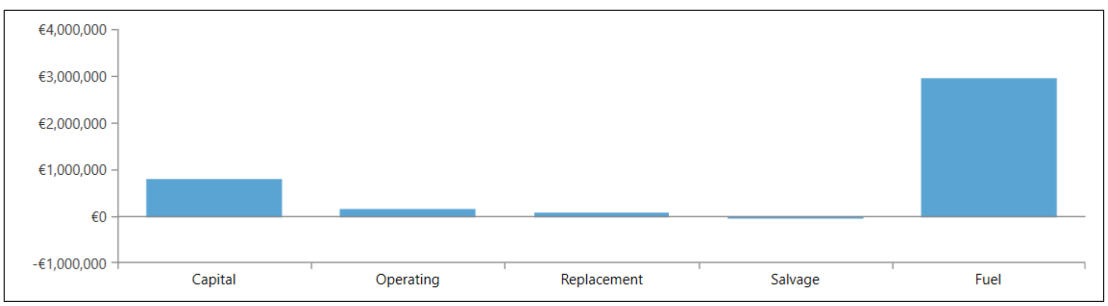

Figure 4.25: Cost summary by Cost Type Scenario 2.

The optimal configuration's components costs and their share on the NPC are highlighted in Figure 4.27. The higher costs come from the conventional unit VOLVO PENTA TAD740GE with 2,071,266.35 € . Subsequently high share in total cost have as well the diesel generator MAN D2566ME with 665,394.93 € of total cost and battery Hoppecke 24 OPzS 3000 with 571,003.60 € . The existence of battery in the selected hybrid system increases the cost, in contrast PV panels and Wind Turbines have not such great share in total cost of the system with 195,567.43 € and 150,340,81 € respectively. Analytical costs by each component are presented in the Figure 4.28 and in Figure 4.29. Each component cost is represented by a different colour during the 20 years of the project lifetime. Replacement costs of Scenario 2 are 112,901.73 € lower than Scenario 1 (175,581.04 €) where 4 out of 5 conventional units are included in the Replacement costs.

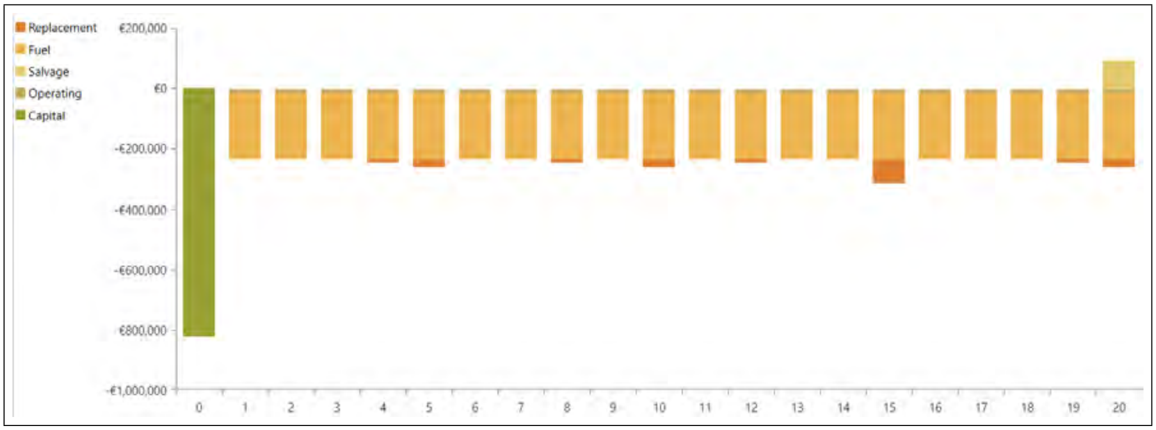

Figure 4.26: Cash flow by Cost Type Scenario 2.

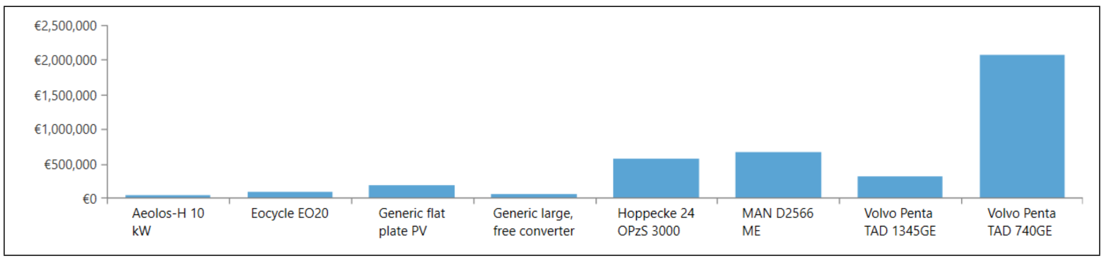

Figure 4.27: Cost summary by Component Scenario 2.

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Aeolos-H 10 kW	€35,800.00	€0.00	€14,357.92	€0.00	€0.00	€50,157.92
Eocycle EO20	€71,600.00	€0.00	€28,582.89	€0.00	€0.00	€100,182.89
Generic flat plate PV	€161,200.00	€0.00	€48,391.49	€0.00	-€14,024.06	€195,567.43
Generic large, free converter	€50,000.00	€24,638.65	€0.00	€0.00	-€13,339.68	€61,298.97
Hoppecke 24 OPzS 3000	€504,000.00	€0.00	€67,003.60	€0.00	€0.00	€571,003.60
MAN D2566 ME	€0.00	€25,803.75	€2,156.08	€639,502.17	-€2,067.07	€665,394.93
Volvo Penta TAD 1345GE	€0.00	€0.00	€1,092.80	€319,589.11	-€4,451.97	€316,229.93
Volvo Penta TAD 740GE	€0.00	€62,459.33	€5,868.40	€2,011,594.91	-€8,656.29	€2,071,266.35
System	€822,600.00	€112,901.73	€167,453.17	€2,970,686.19	-€42,539.07	€4,031,102.03

Figure 4.28: Analytical costs of each component Scenario 2.

In Scenario 1 (Section 4.1.1) the cost for the existing power of Donoussa was assumed after the total cost of one year of operation was calculated almost at 5,063,705.06 €. The total NPC cost of the optimal configuration of this Scenario is 4,031,102 € lower than cost of Scenario 1 and calculated cost of existing power system. Scenario 2 is considered the most economical feasible among Scenario 1 and existing power system with a 0% of Excess Electricity. Almost 1 million of Euros is saved by this hybrid system configuration and the load is fully satisfied.

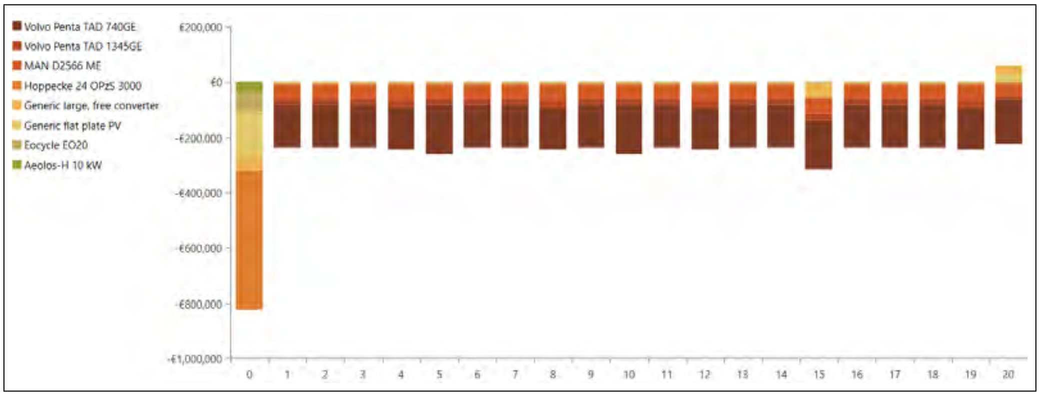

Figure 4.29: Cost summary by Component Scenario 2.

4.1.3 Scenario 3/Wind-PV-Battery

Scenario 3 is composed of a 100% renewable hybrid system. As it was observed by Scenarios 1 and Scenario 2, is possible for the system to meet the island's load demands with the least number of conventional units. As a result of this in the third simulated scenario, all diesel generators were removed from the simulations in order to be discovered if a 100% renewable hybrid system is feasible from a technical point of and of a economic point of view. A base load power is considered the power that is always available by the power system to satisfy the minimum amount of electricity demand for customers. Most common power plants which serve the base load have some common characteristics like the generation of electricity almost constant power, a high capacity factor demand, output stability and reliable operation. [13] In off-grid, autonomous power systems like power system in Donoussa island, conventional units are responsible for this kind of power. A 100% renewable, off-grid system could face a lack of capacity to supply electricity for the base load due to the absence of a constant power source in order to meet the load. In addition, the intermittent nature of RES could have a huge effect on the configuration of the system. In this scenario 2 cases are going to be examined: one case with 1260 batteries and one with 2112 batteries. All the scenarios were simulated in respect with the lowest Excess Electricity that can be achieved. For that reason only one feasible system is resulted from the simulations for case 1 (1260 batteries) and 1 for case 2 (2112 batteries). In both cases the only feasible system will be considered the optimal. In Table 4.15 and 4.16 are presented the optimal systems for each case. For the first case the optimal system includes 1450 kW of PV panels, 7 Wind Turbines (Aeolos-H 10 kW), 1260 Battery units and a 470 kW converter. The optimal system configuration selected a Cycle Charging dispatch strategy (CC). The other optimal system consists of 1450 kW of PV panels, 2 Wind Turbines (Aeolos-H 10 kW), 2112 battery units and a 450 kW converter. A Load Following (LF) dispatch strategy was selected for the optimal system for this case. The NPC (Net Present Cost) is at 3,759,814.85 € and LCoE at 0.2241 € for case 1 and for case 2 NPC is 5,217,030.15 € and LCoE is 0.3107 €. In two cases optimal system, the rated capacity of renewables increased to 1520 kW and 1470 kW for cases 1 and 2 respectively of Scenario 3. In general the increase of renewables and battery storage compared to the previous Scenarios is enormous. In Scenario 1 the rated capacity of RES was 140 kW, in Scenario 2 was 300 kW. The increase that was observed is at least 950 % compared to Scenario 1 and 390% compared to Scenario 2. The increase in battery storage in comparison to Scenario 2 is almost 200% for case 1 of Scenario 3 and 403% for case 2 of Scenario 3. The increase in battery storage was considered necessary due to the fact that RES are intermittent and generate at less than their maximum potential capacity making the need for higher installed power capacity. Another major concern of a 100% renewable off-grid hybrid system is that is not possible and easy to predict the exact time and exact quantity of power delivery to customers. Thus high capacity of energy storage and large quantities of batteries are vital for the hybrid system of Scenario 3. However two systems face the problem of the unmet electrical load and the Capacity shortage at a very small percentage. For case 1 are 1,033 kWh/yr (0.0818%) and 1,259 kWh/yr (0.0997%) for Unmet Electric Load and Capacity Shortage respectively and as for case 2 are 103 kWh/yr (0.00810%) and 283 kWh/yr (0.0224%). The percentage in both cases is low but in case 2 are almost at zero rate. It can be easily justified from the fact that in case 2 battery storage is of a greater capacity than case 1 (2112 to 1260 battery units). Battery is able to provide the customers the energy during the time RES do not operate. Greater battery capacity offers in the hybrid system more days of autonomy. Furthermore, the percentage of Unmet Electric Load and Capacity Shortage in both cases is almost minimum and it is considered easily manageable. Table 4.17 and 4.18 present the technical and electrical characteristics of the optimal system for case 1 and case 2 of Scenario 3.

Table 4.15: Scenario 3 (Case 1-1260 Batteries) Optimization results.

Systems	PV (kW)	Aeolos-H	Battery	Conv (kW)	Excess Elec (%)	NPC (Millions €)	COE (€)	Dispatch
System 1	1,450	7	1260	470	46.8	3.76	0.224	LF

Table 4.16: Scenario 3 (Case 2-2112 Batteries) Optimization results.

Systems	PV (kW)	Aeolos-H	Battery	Conv (kW)	Excess Elec (%)	NPC (Millions €)	COE (€)	Dispatch
System 1	1,450	2	2112	450	41.8	5.22	0.311	CC

Table 4.17: Analytical Electrical Production and technical characteristics for optimal configuration of Scenario 3 case 1.

System Components	Size	Electricity production		Mean Output (kW)	Operational hours (hrs/yr)
		kWh/yr	%		
PV	1450 kW	2,390,365	90.2	273	4,386
Aeolos-H (10 kW)	7 (70 kW)	261,025	9.84	29.8	7,374
Total	1,520	2,651,391	100	-	-
Battery Hoppecke	1260 (9,009 kWh)	Energy in 678,208 kWh/yr	Energy out 583,614 kWh/yr	Annual through-put 629,327 kWh/yr	Autonomy 43.7 hr

From Tables 4.17 and 4.18 some useful remarks are able to be derived. In two optimal configurations for the two cases of Scenario 3 it is easily noticed that PV panels have a greater share of energy production and Wind turbines among with the battery complete the production and the delivery of the energy in the hybrid system. In both cases rated capacity of PV panels is the same. As it can be seen from Table 4.17 and 4.18 in case 2 the percentage of participation of PV panels in the total production is greater than in case 1 due to the fact that rated capacity of Wind Turbines is less in case 2 than in case 1 (20 kW in case 2, 70 kW in case 1). PV panels in both cases are the main source of the supply of electricity in a stable way to Donoussa island due to the fact that their production is more predictable. Monthly electrical

Table 4.18: Analytical Electrical Production and technical characteristics for optimal configuration of Scenario 3 case 2.

System Components	Size	Electricity production		Mean Output (kW)	Operational hours (hrs/yr)
		kWh/yr	%		
PV	1450 kW	2,390,365	97	273	4,386
Aeolos-H (10 kW)	2 (20 kW)	74,579	3.03	8.51	7,374
Total	1,470	2,464,944	100	-	-
Battery Hoppecke	2112 (15,099 kWh)	Energy in 783,923 kWh/yr	Energy out 674,837 kWh/yr	Annual throughput 727,696 kWh/yr	Autonomy 73.3 hr

production of each component is depicted 4.30 and 4.31 for the two cases. In general, solar energy is a more predictable and stable source of energy than wind energy which has more intermittent and unpredictable nature. Donoussa has great percentage of solar irradiation during the year and PV panels for a 100% Renewable scheme is considered a reliable source of energy. PV power output and PV scheme simulation results are highlighted in Table 4.19 and Figure 4.32 for both cases.

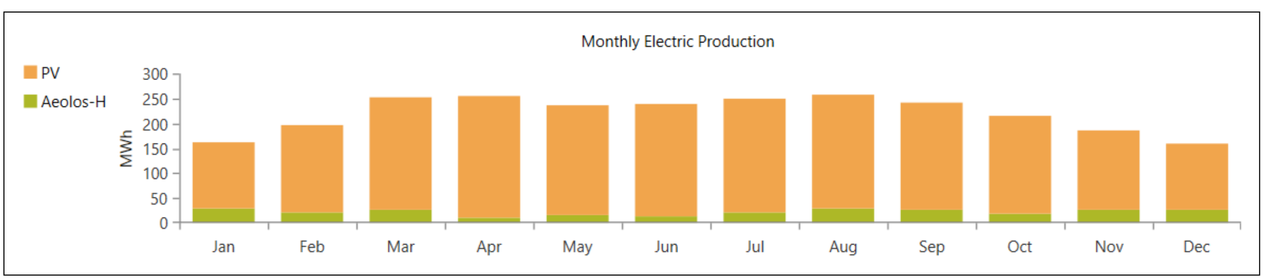

Figure 4.30: Monthly electrical Production Case 1 Scenario 3.

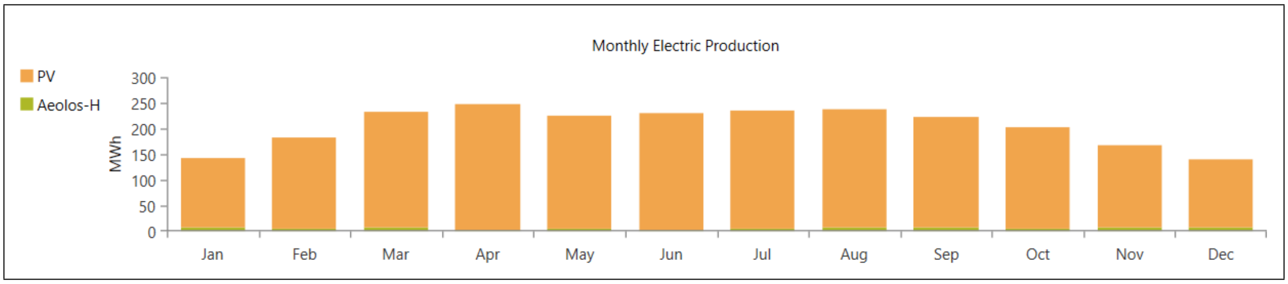

Figure 4.31: Monthly electrical Production Case 2 Scenario 3.

Table 4.19: PV Scheme Simulation Results Case 1 and Case 2, Scenario 3.

Quantity	Value	Units
Rated capacity	1,450	kW
Minimum Output	0	kW
Maximum Output	1,285	kW
Mean Output	273	kW
Mean Output	6,549	kWh/d
Capacity Factor	18.8	%
Total Production	2,390,365	kWh/yr
PV Penetration	189	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0343	€/kWh

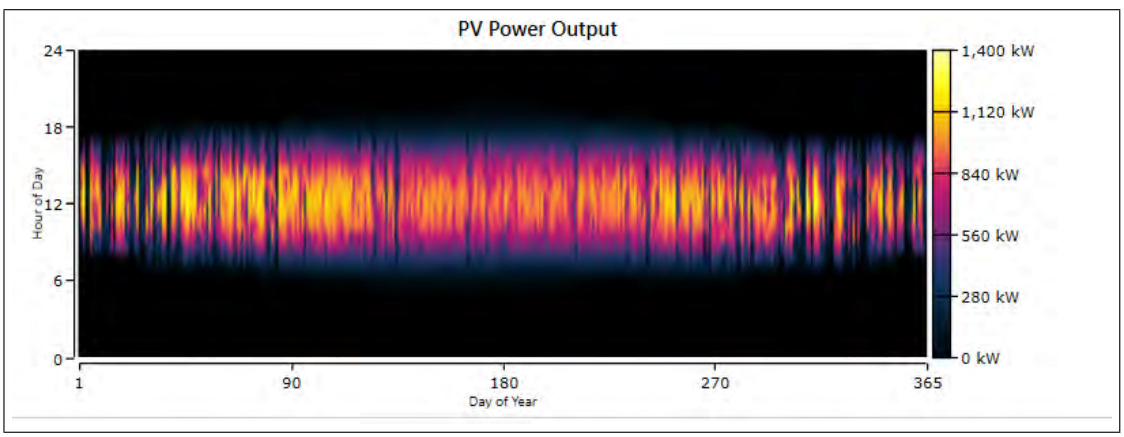

Figure 4.32: PV power output Case 1 and Case 2 Scenario 3.

Wind Turbines have a more "auxiliary" role in the Scenario 3 in both cases. This fact can be confirmed from the contribution of them in the electrical production with 9.84% for Case 1 and 3.03% for Case 2. In Case 1 70 kW (7 units of Aeolos-H 10 kW) are included in the optimal system configuration and in Case 2 20 kW (2 units of Aeolos-H of 10 kW). January, March and July are the months that the maximum power output of Wind Turbine is met. Aeolos-H power output for Case 1 and Case 2 is presented in Figures 4.33 and 4.34 below. Table 4.20 and 4.21 depict the Wind Turbine Scheme simulation results for the two cases of Scenario 3. The differences between the two cases are justified from the different installed capacity for the two cases.

Table 4.20: Aeolos-H (10 kW) Scheme Simulation Results Case 1 Scenario 3.

Quantity	Value	Units
Rated capacity	70	kW
Minimum Output	0	kW
Maximum Output	96.6	kW
Mean Output	29.8	kW
Capacity Factor	42.6	%
Total Production	261,025	kWh/yr
Wind Penetration	20.7	%
Hours of Operation	7,374	hrs/yr
Levelized Cost	0.0506	€/kWh

Table 4.21: Aeolos-H (10 kW) Scheme Simulation Results Case 1 Scenario 3.

Quantity	Value	Units
Rated capacity	20	kW
Minimum Output	0	kW
Maximum Output	27.6	kW
Mean Output	8.51	kW
Capacity Factor	42.6	%
Total Production	74,579	kWh/yr
Wind Penetration	5.90	%
Hours of Operation	7,374	hrs/yr
Levelized Cost	0.0506	€/kWh

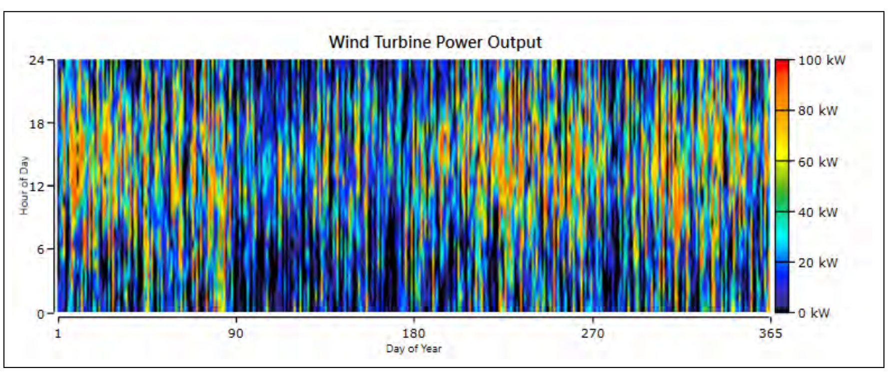

Figure 4.33: Wind power output Case 1 Scenario 3.

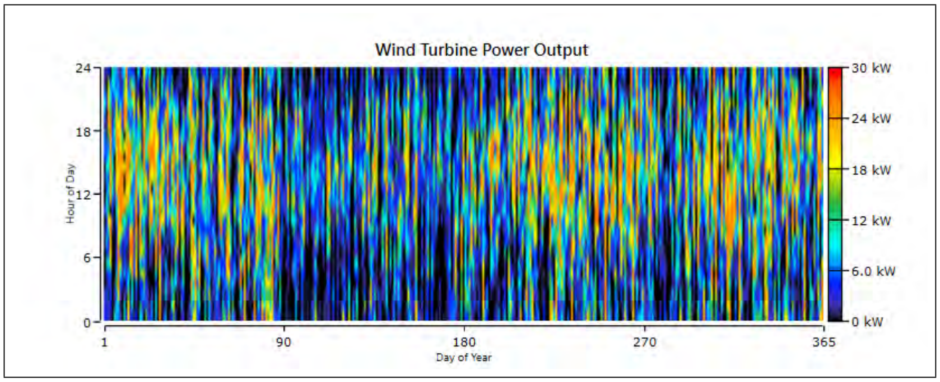

Figure 4.34: Wind power output Case 2 Scenario 3.

Another parameter for the two optimal hybrid systems for Scenario 3 is the battery. In case 1 1,260 units of Hoppecke 24 OPzS 3000 (7.15 kWh per battery) and in case 2 were included 2,160 units of battery. The days of autonomy were considered 3 for the first case and 5 for the second case. There is a great difference in capaicty of the two battery units with 9,009 kWh for case 1 in contrast with 15,099 kWh for case 2. Between the two cases battery makes hybrid system more stable and this can be derived from the Unmet Electric Load Capacity Shortage as mentioned earlier as well as from the Excess Electricity between the two cases (Table 4.15 and 4.16). Case 2 has 2,112 units so Excess Electricity is 41.8% and for Case 1 (1260 units) the Excess Electricity percentage touches almost half of the energy output with 46.8%. More battery units offer more autonomy, flexibility and stability. Battery scheme simulation results can be seen in Tables 4.22 and 4.23. In Figures 4.35 and 4.36 State-of-Charge for each case is highlighted. In both cases the battery units are in low levels of charge during summer month until September. It is concluded from both figures that the time period that battery of Case 1 (1260 units) is at minimum state of charge keeps less time than state of charge in Case 2. The greater capacity of Case 2 in order to support the RES for the load demands that arise summer months and more specifically in August when peak load happen, battery stays at low levels of charge. On the other hand for battery in Case 1 (1260 units), during summer months until September stays at medium levels of charge and is discharged to minimum (30%) during the peak load period.

Table 4.22: Battery Scheme Simulation Results Case 1 Scenario 3.

Quantity	Value	Units
Batteries	1,260	qty
String Size	12.0	batteries
Strings in Parallel	105	strings
Bus Voltage	24.0	V
Autonomy	43.7	hr
Storage Wear Cost	0.0895	€/kWh
Nominal Capacity	9,008	kWh
Usable Nominal Capacity	6,306	kWh
Energy In	678,208	kWh/yr
Energy Out	583,614	kWh/yr
Storage Depletion	383	kWh/yr
Losses	94,977	kWh/yr
Annual Throughput	629,327	kWh/yr

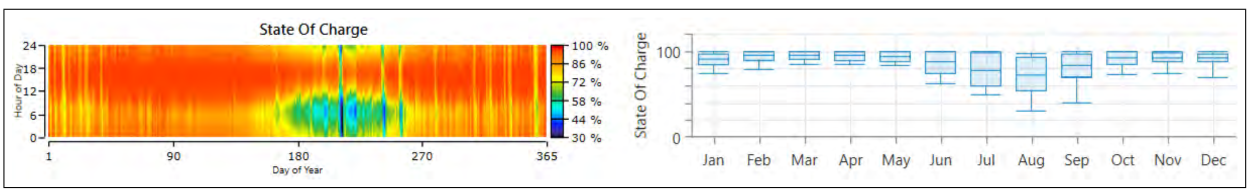

Figure 4.35: Battery State-of-Charge Case 1 Scenario 3.

Table 4.23: Battery Scheme Simulation Results Case 2 Scenario 3.

Quantity	Value	Units
Batteries	2,112	qty
String Size	12.0	batteries
Strings in Parallel	176	strings
Bus Voltage	24.0	V
Autonomy	73.3	hr
Storage Wear Cost	0.0895	€/kWh
Nominal Capacity	15,099	kWh
Usable Nominal Capacity	10,569	kWh
Energy In	783,923	kWh/yr
Energy Out	674,837	kWh/yr
Storage Depletion	715	kWh/yr
Losses	109,801	kWh/yr
Annual Throughput	727,696	kWh/yr

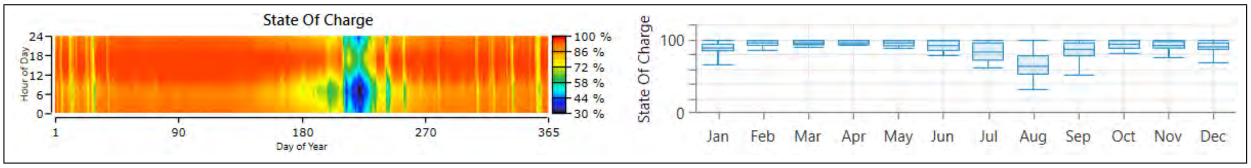

Figure 4.36: Battery State-of-Charge Case 2 Scenario 3.

The renewable penetration of the two cases that are examined in this scenario is of a great amount. The Maximum Renewable Penetration is 7,584 % and 7,496 % for both cases respectively. Moreover, a 100% Renewable hybrid system has a tremendous merit of having zero fuel emissions. A hybrid system like this without the presence of conventional units is environmental friendly, without fuel emissions and pollutants in the atmosphere which may affect the natural environment of island.

Technical difficulties are not the only obstacles that a 100% renewable hybrid system could face up. Infrastructure costs are important and the implementation of high capacities renewable energy sources for the satisfaction of the load of a small island would result in high costs and expenses. The economic aspects and costs of the two cases of this scenario are going to be examined below. Firstly the NPC is at 3,759,814.85 € and LCoE at 0.2241 € for case 1 and for case 2 NPC is 5,217,030.15 € and LCoE is 0.3107 €. Compared to NPC and LCoE costs of the previous scenarios case 1 has lower cost than Scenario 1 (4,950,407.61 € and 0.2948 €) and Scenario 2 (4,031,102 € and 0.2401 €). On the other hand Case 2 of Scenario 3 has higher costs than other two scenarios. Table 4.24 and Table 4.25 summarize the financial aspects of the optimal configuration of the two studies cases of Scenario 3. Cost summaries by cost type for Scenario 3 are illustrated in Figure 4.37 and 4.38.

Table 4.24: Economic characteristics of the optimal configuration of Case 1 Scenario 3.

System	NPC (€)	LCoE (€)	Capital (€)	Replacement (€)	Salvage (€)	O & M (€/yr)
Optimal	3,759,815	0.2241	2,653,800	57,900.82	-109,559.34	1,157,673.37

Table 4.25: Economic characteristics of the optimal configuration of Case 2 Scenario 3.

System	NPC (€)	LCoE (€)	Capital (€)	Replacement (€)	Salvage (€)	O & M (€/yr)
Optimal	5,217,030.15	0.3107	3,581,700	55,436.96	-108,225.38	1,688,118.57

In both cases the main core of costs of the system is the Capital costs and then the Operating and Maintenance Cost. The Capital cost of Case 2 is clearly higher due to the greater capacity of battery (2,653,800 € for Case 1 and 3,581,700 for Case 2). In comparison with Scenario 1 and Scenario 2 Capital Cost is much higher and this is due to the increase in capacity of renewables. Furthermore, in Scenario 1 and Scenario 2 the main source of the costs of the system were the fuel for the operation of the Diesel generators. Scenario 1 and 2 due to the existence of diesel generators are highly dependent on the price of diesel which is not stable. Operating and Maintenance costs in Scenario 3 are of a great share in the total

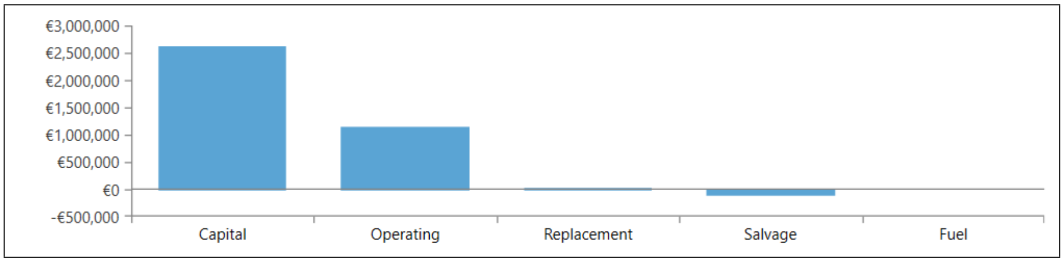

Figure 4.37: Cost summary by Cost Type Case 1 Scenario 3.

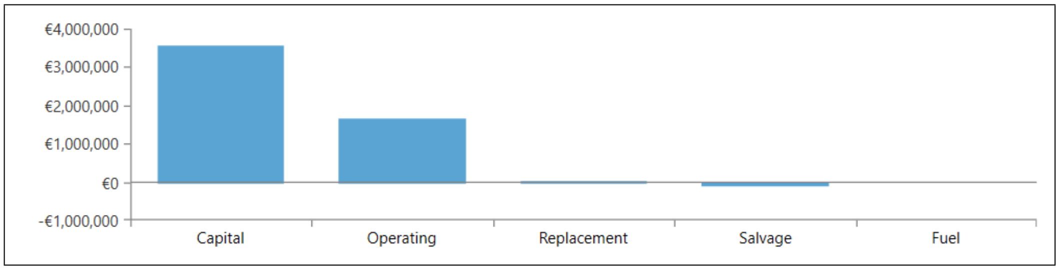

Figure 4.38: Cost summary by Cost Type Case 2 Scenario 3.

NPC cost (1,157,673.37 € Case 1 and 1,688,118.57 €). The fact that in Scenario 1 and in Scenario 2 Operating and Maintenance costs were 62,424.89 € and 167,453.17 € , shows the huge difference between them. Consequently Operating and Maintenance costs of a larger capacity of RES are way more expensive. Cash flow by cost type during the 20 years of the project for Scenario 3 are depicted in Figure 4.39 and 4.40.

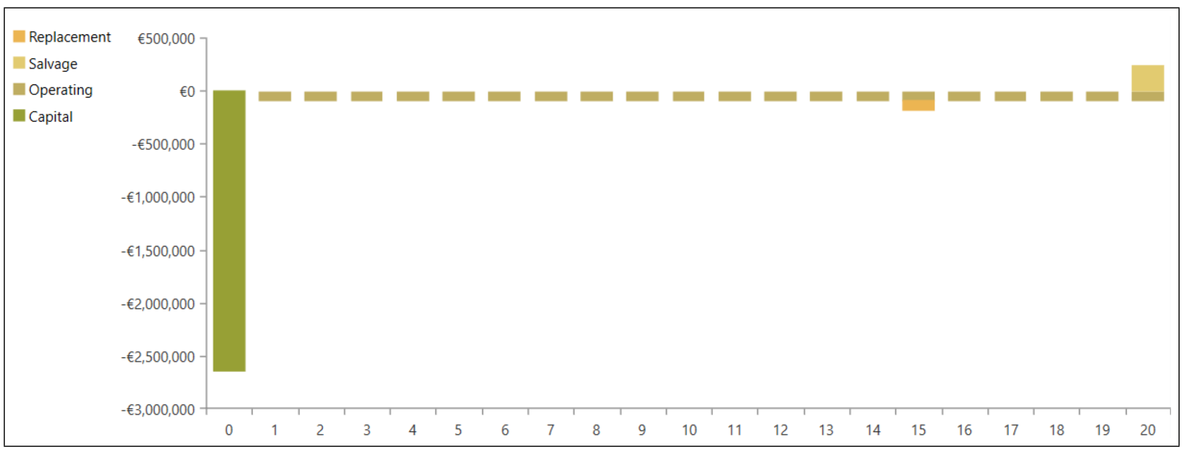

Figure 4.39: Cash flow summary by Cost Type Case 1 Scenario 3.

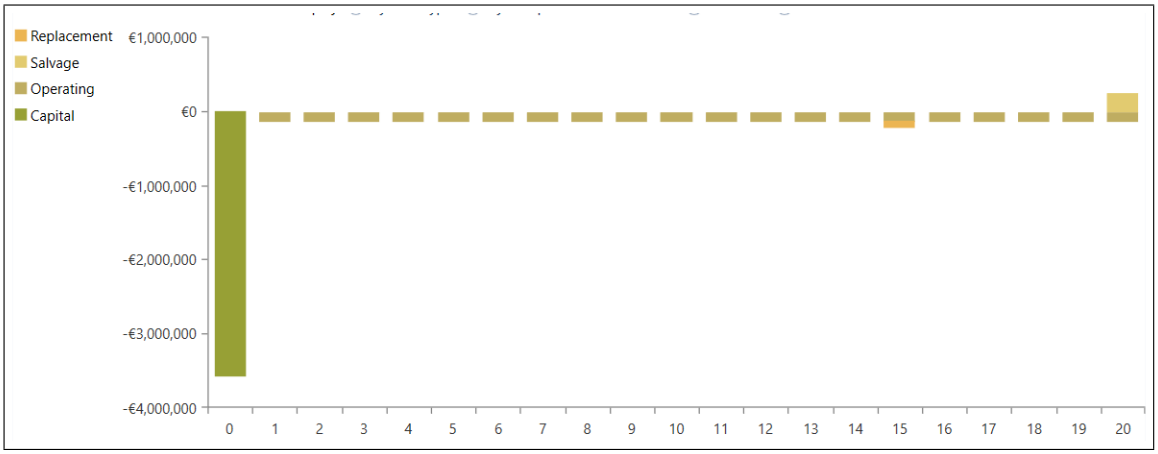

Figure 4.40: Cash flow summary by Cost Type Case 2 Scenario 3.

Additionally, as it mentioned earlier Battery is the most expensive component of the hybrid system for both cases. Especially in Case 2 where Battery units is almost double than Case 1 confirm the fact that size of the battery bank is of a great importance on optimising the hybrid system. Cost summary and detailed costs of the cost of each component for both cases are presented in Figure 4.41, 4.42, 4.43 and 4.44. By Figures below it is confirmed that battery bank is the most expensive component and has a serious effects on the NPC of the hybrid systems. Moreover, the costs of the optimal hybrid systems configuration are depicted in Figures 4.45 and 4.46 where is depicted the cost of each component by different colour during lifetime of the project. Battery again is confirmed to be the most expensive component of the hybrid system as far as Capital Cost and Operating and Maintenance Costs are concerned.

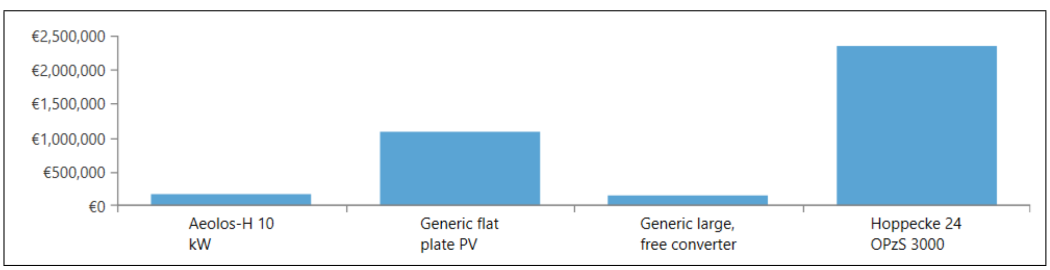

Figure 4.41: Cost summary by Component Case 1 Scenario 3.

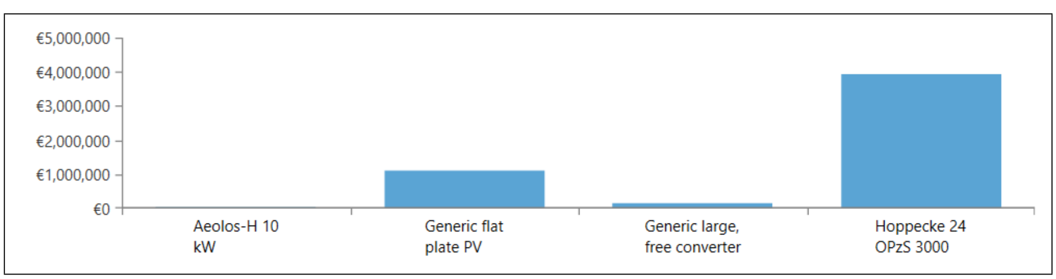

Figure 4.42: Cost summary by Component Case 2 Scenario 3.

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Aeolos-H 10 kW	€35,800.00	€0.00	€14,357.92	€0.00	€0.00	€50,157.92
Generic flat plate PV	€899,000.00	€0.00	€269,875.63	€0.00	-€78,211.10	€1,090,664.52
Generic large, free converter	€112,500.00	€55,436.96	€0.00	€0.00	-€30,014.27	€137,922.69
Hoppecke 24 OPzS 3000	€2,534,400.00	€0.00	€1,403,885.03	€0.00	€0.00	€3,938,285.03
System	€3,581,700.00	€55,436.96	€1,688,118.57	€0.00	-€108,225.38	€5,217,030.15

Figure 4.43: Analytical costs of each component Case 1 Scenario 3.

Component	Capital (€)	Replacement (€)	O&M (€)	Fuel (€)	Salvage (€)	Total (€)
Aeolos-H 10 kW	€125,300.00	€0.00	€50,252.70	€0.00	€0.00	€175,552.70
Generic flat plate PV	€899,000.00	€0.00	€269,875.63	€0.00	-€78,211.10	€1,090,664.52
Generic large, free converter	€117,500.00	€57,900.82	€0.00	€0.00	-€31,348.24	€144,052.58
Hoppecke 24 OPzS 3000	€1,512,000.00	€0.00	€837,545.05	€0.00	€0.00	€2,349,545.05
System	€2,653,800.00	€57,900.82	€1,157,673.37	€0.00	-€109,559.34	€3,759,814.85

Figure 4.44: Analytical costs of each component Case 2 Scenario 3.

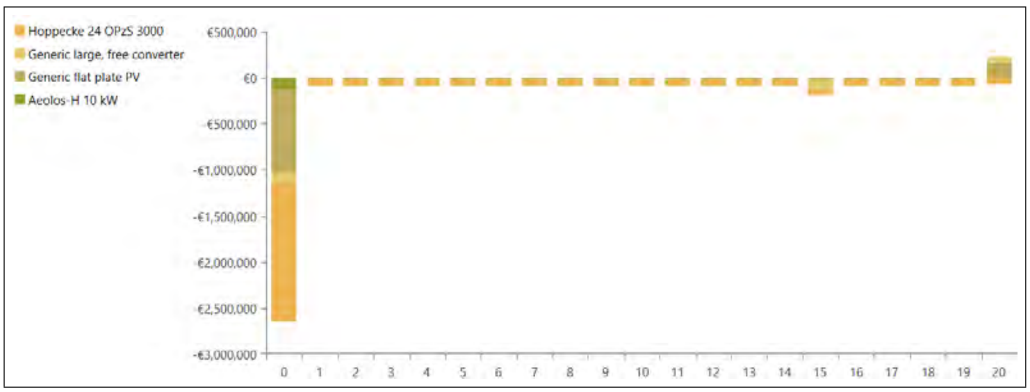

Figure 4.45: Cash flow summary by Component Case 2 Scenario 3.

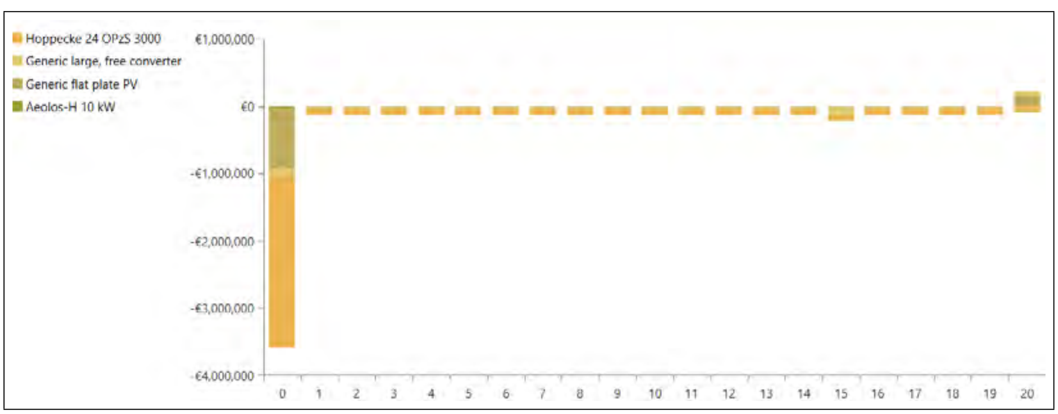

Figure 4.46: Cash flow summary by Component Case 2 Scenario 3.

As for the long-term scenario of the total cost of existing power system of Donoussa, as it mentioned in Section 4.1.1 and 4.1.2, its cost is 5,063,705.06 €. Case 1 is more economically advantageous withn NPC of 3,759,815 € , while Case 2 with 5,217,030.15 € of NPC cost is not financially feasible. On the other hand it can support power system of Donoussa in a more stable way and and the Excess Electricity percentage is less than Case 1. Nevertheless both systems provide a 100% renewable and green solution for the electrification of Donoussa island.

4.2 Sensitivity Analysis Results

Sensitivity analysis is performed in order to investigate the impact of the variation of the input parameters and variables on the behavior of the system and to identify the most sensitive parameters. [46] In this study a sensitivity analysis is going to be performed in order to be studied the affect of the sensitivity variables on the optimal configuration system of each scenario. For Scenario 1 and 2 a sensitivity analysis is examined with a 20% increase and decrease in the price of diesel fuel. For Scenario 3 a chnage of 20% in the natural resources (solar irradiation and wind speed) is applied to the optimal system configuration.

As mentioned above for Scenario 1 a change in the price of diesel was assumed in the optimal system configuration. In Table 4.26 are presented the Sensitivity Analysis results for Scenario 1. Main conclusion by the Table 4.26 and sensitivity analysis is that NPC and LCoE values of the optimal hybrid system of Scenario 1 increase with increasing diesel price in a great rate and decrease with decreasing diesel price. Figure 4.47 shows the variation of NPC cost and LCoE depending on different values of diesel price. The increase in the NPC cost and LCoE of optimal system is proportional of the increase of diesel price. Especially this can be justified from the fact that five diesel generator units are included in Scenario 1. In the base case the diesel price is 1.387 € , there is a sharp increase from 4.95 to 5.87 for a 20% increase in the diesel price. Fuel costs in the increase of diesel price are 5,495,633.08 € while for the base case (1.387 € diesel price) fuel costs are 4,595,337.32 € and a decrease in diesel price results in the decrease of almost 1 million € at fuel costs (3,696,439.55 €). Finally, as it can be seen from Table 4.25 the impact on Excess Electricity is almost negligible and this factor seem not to be affected from the variations on diesel price.

Table 4.26: Scenario 1 Sensitivity results.

Diesel Price (€)	PV (kW)	EO20 (WT)	TAD 740GE (kW)	TAD 1345GE (kW)	TAD 1345GE (kW)	D2566 ME (kW)	D2566 ME (kW)	Conv (kW)	Excess Elec. (%)	NPC (Millions €)	COE (€)	Ren Frac (%)	Dispatch
1.110	100	2	200	250	250	80	80	80	6.67	4.03	0.240	20.2	CC
1.387	100	2	200	250	250	80	80	80	6.68	4.95	0.295	20.2	CC
1.664	100	2	200	250	250	80	80	80	6.70	5.87	0.349	20.1	CC

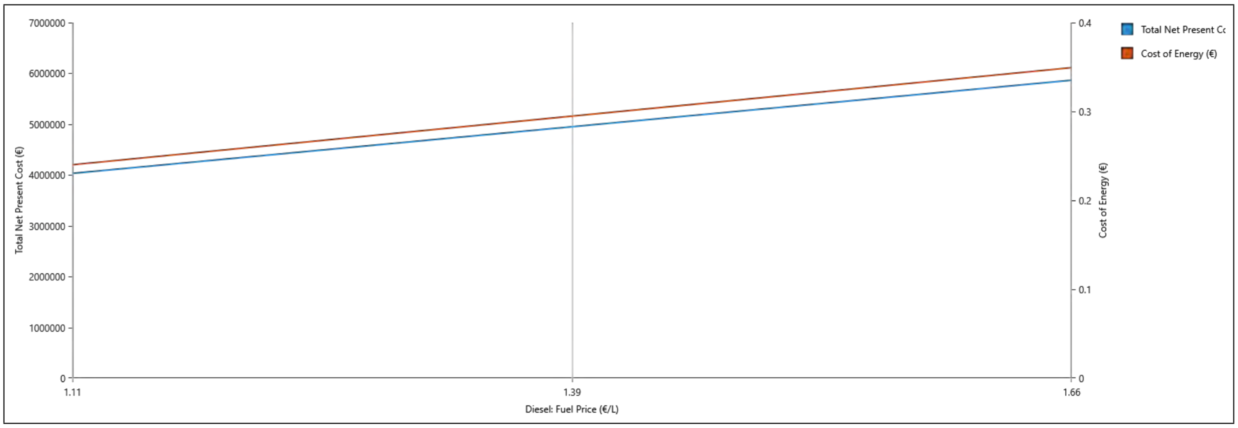

Figure 4.47: Effects of variation of diesel price to NPC and CoE.

In Scenario 2 a sensitivity analysis is performed in order to be studied the impact that has on the optimal system configuration the variation on diesel price and in variation of wind speed. In Table 4.26 are highlighted the sensitivity results for Scenario 2 (all system configuration use Load Following dispatch strategy). Increase in the wind speed by 20% has an impact on the decrease of the NPC and CoE as it can be derived from Table 4.27. Figures 4.48 and 4.49 below show the variation in the NPC cost and LCoE according to variations in diesel price and wind speed. Moreover, the increase in the wind speed has an little impact in the Excess Electricity which changes in a small percentage. The increase in diesel price in combination with the standard average wind (7.10 m/s), have a negative impact on NPC and LCoE as both parameters increase. The reduction of conventional units in this Scenario 3 makes the hybrid system feasible technically and financially despite the variations in diesel price and wind speed.

Table 4.27: Scenario 2 Sensitivity results.

Diesel Price (€)	Wind Speed	PV (kW)	EO20 (WT)	Aeolos-H (WT)	TAD 740GE (kW)	TAD 1345GE (kW)	D2566 ME (kW)	Battery	Conv (kW)	Excess Elec. (%)	NPC (Millions €)	COE (€)	Ren Frac (%)
1.110	7.10	260	2	2	200	250	80	420	200	0	3.44	0.205	51
1.110	8.52	260	2	2	200	250	80	420	200	0.019	3.26	0.194	54.6
1.387	7.10	260	2	2	200	250	80	420	200	0	4.03	0.240	51
1.387	8.52	260	2	2	200	250	80	420	200	0.019	3.81	0.227	54.6
1.664	7.10	260	2	2	200	250	80	420	200	0	4.63	0.276	51
1.664	8.52	260	2	2	200	250	80	420	200	0.019	4.36	0.260	54.6

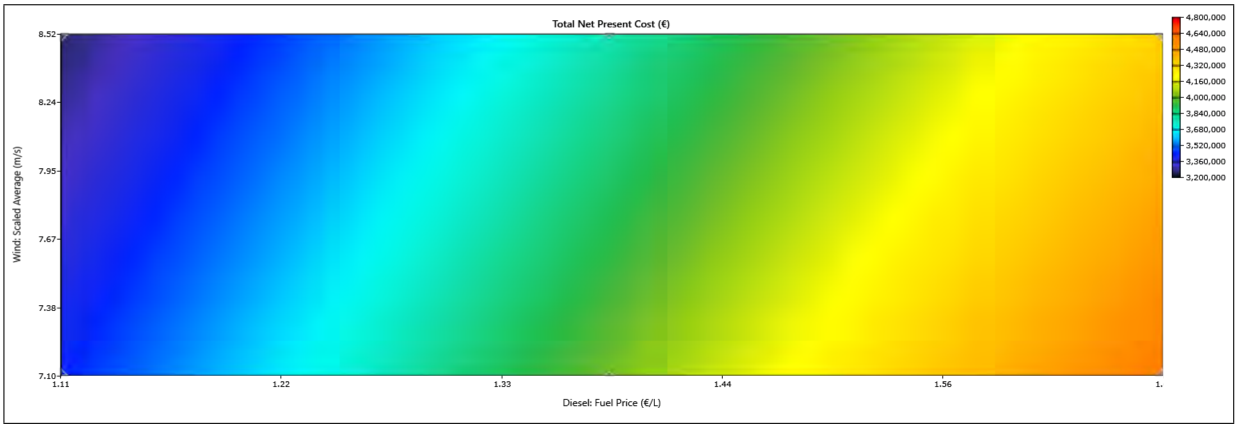

Figure 4.48: Effects of variation of diesel price and wind speed to NPC.

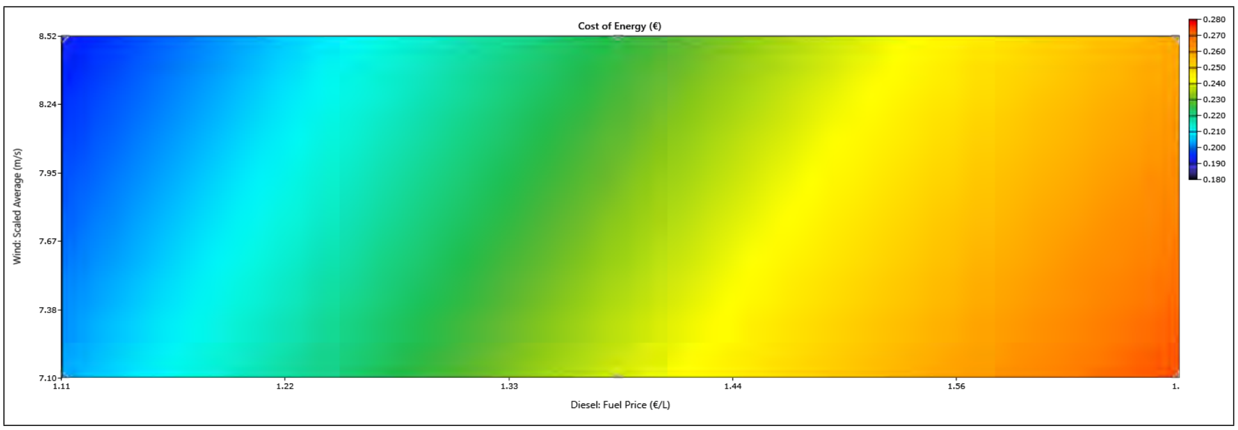

Figure 4.49: Effects of variation of diesel price and wind speed to CoE.

Scenario 3 is the 100% renewable hybrid system scenario. In Table 4.28 below are depicted the sensitivity analysis results for Case 1 of Scenario 3. Only feasible cases are presented, on this optimal configuration some cases are not feasible (with average solar irradiation 4.336 kWh/m^2/day and the case with solar irradiation of 5.42 Wh/m^2/day in combination with wind speed of 5.68m/s). As a result of this in Table 4.27 only five out of nine configurations are shown. From Table 4.27 it can be easily derived that the increase of solar irradiation in combination with the increase of average wind speed has no impact on the increase or the decrease of NPC cost and CoE. On the other hand there is a gradual increase in the Excess Electricity parameter which is an important factor for the smooth operation of the hybrid system. Figure 4.50 depict the increase of the Excess Electricity in combination with the variations of the solar irradiation and wind speed. The increase in the natural resources make RES components to produce more energy that is not able to be stored so the Excess Electricity percentage increases.

Table 4.28: Scenario 3 Case 1 Sensitivity results.

Solar irradiation	Wind Speed	PV (kW)	Aeolos-H (WT)	Battery	Conv (kW)	Excess Elec. (%)	NPC (Millions €)	COE (€)
5.42	7.10	1450	7	1260	470	46.8	3.76	0.224
5.42	8.52	1450	7	1260	470	48.6	3.76	0.224
6.50	5.68	1450	7	1260	470	51.4	3.82	0.227
6.50	7.10	1450	7	1260	470	53.2	3.76	0.224
6.50	8.52	1450	7	1260	470	54.7	3.76	0.224

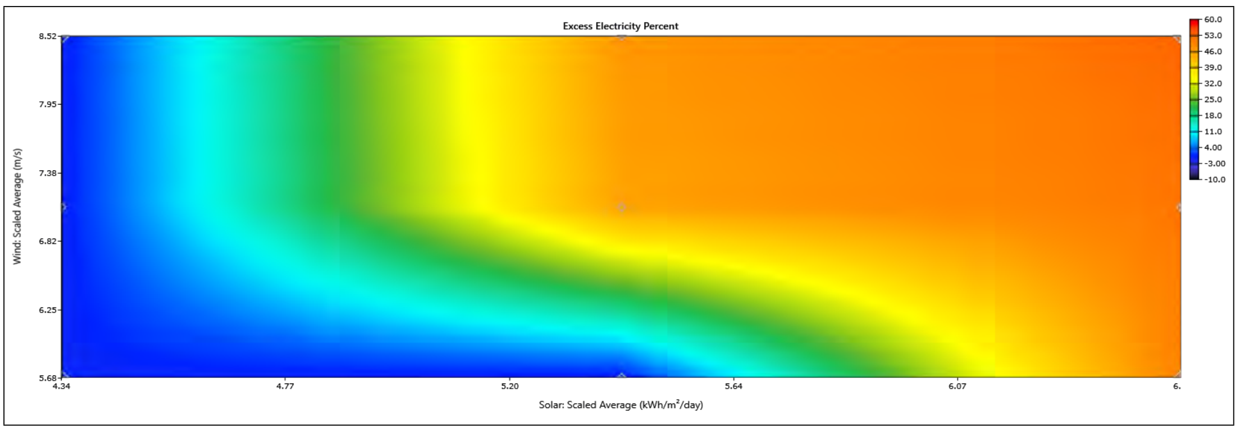

Figure 4.50: Effects of variation of solar irradiation and wind speed to Excess Electricity Case 1.

For Case 2 of Scenario 3 (2112 battery units) sensitivity results are almost similar to results of Case 1 of Scenario 3. Five out of nine configurations are feasible and four out of nine are considered insufficient. Table 4.29 shows the sensitivity analysis results of Case 2 of Scenario 3. NPC and LCoE are stable and the same in all five systems. Excess Electricity has the same behaviour like Case 1 of Scenario 2, with a gradual increase. This gradual increase occurs during the increase of the natural resources (wind speed and solar irradiation) and reaches almost 50% which is less percentage than Case 1 of Scenario 3. This can be justified from the greater capacity of the battery bank (2112 batteries in Case 2 in contrast with the 1260 batteries of Case 1). Excess Electricity percentage in relation with sensitivity variables of Case 2 is depicted in Figure 4.51.

Table 4.29: Scenario 3 Case 2 Sensitivity results.

Solar irradiation	Wind Speed	PV (kW)	Aeolos-H (WT)	Battery	Conv (kW)	Excess Elec. (%)	NPC (Millions €)	COE (€)
5.42	7.10	1450	2	2112	450	41.8	5.22	0.311
5.42	8.52	1450	2	2112	450	42.4	5.22	0.311
6.50	5.68	1450	2	2112	450	48.7	5.22	0.311
6.50	7.10	1450	2	2112	450	49.3	5.22	0.311
6.50	8.52	1450	2	2112	450	49.8	5.22	0.311

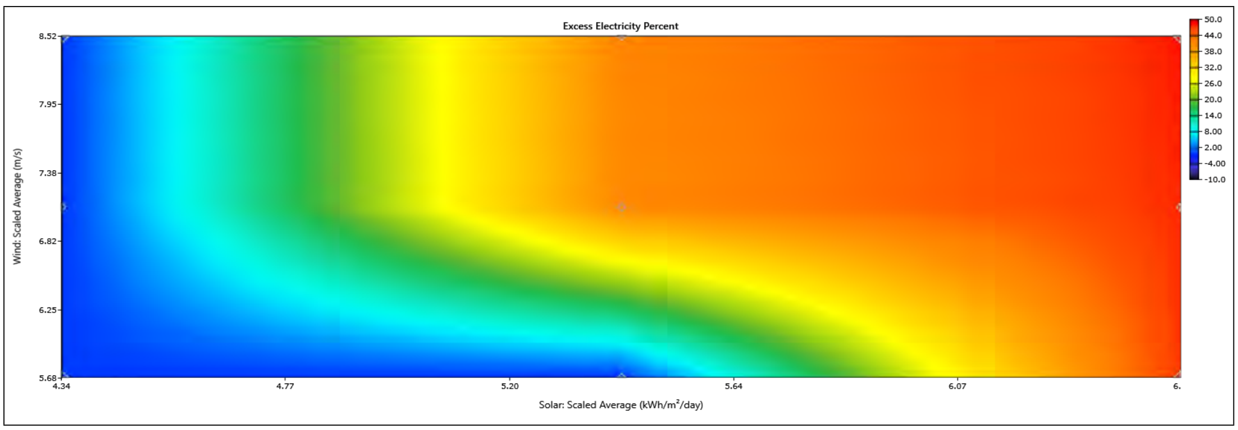

Figure 4.51: Effects of variation of solar irradiation and wind speed to Excess Electricity Case 2.

4.3 Excess Electricity Assessment

A serious parameter that was taken into consideration in this thesis was Excess Electricity of the different hybrid systems. One of the main targets of this study was at first the zero percentage of Excess Electricity in different hybrid system scenarios and then if this was not possible the maximum reduction of the Excess Electricity percentage to the extent that it would make the hybrid system. As for the 100% renewable scenario, it cannot be avoided the existence of a abundant percentage of Excess Electricity due to the fact that energy storage component is not included in this scenario. According to Optimization results the percentage of Excess Electricity of Scenario 1 was 6.68% (90,807 kWh/yr). This percentage is small but not negligible and can cause stability problems and network overload problems. The Excess Electricity daily profile of Scenario 1 can be seen in the Figure 4.52. Months with intense production of Excess Electricity is January, February, March, April, November and December. It can be concluded that natural resources like wind speed and solar irradiation outweigh the installed capacity of RES and the extra energy can not be stored due to lack of battery of the hybrid system.

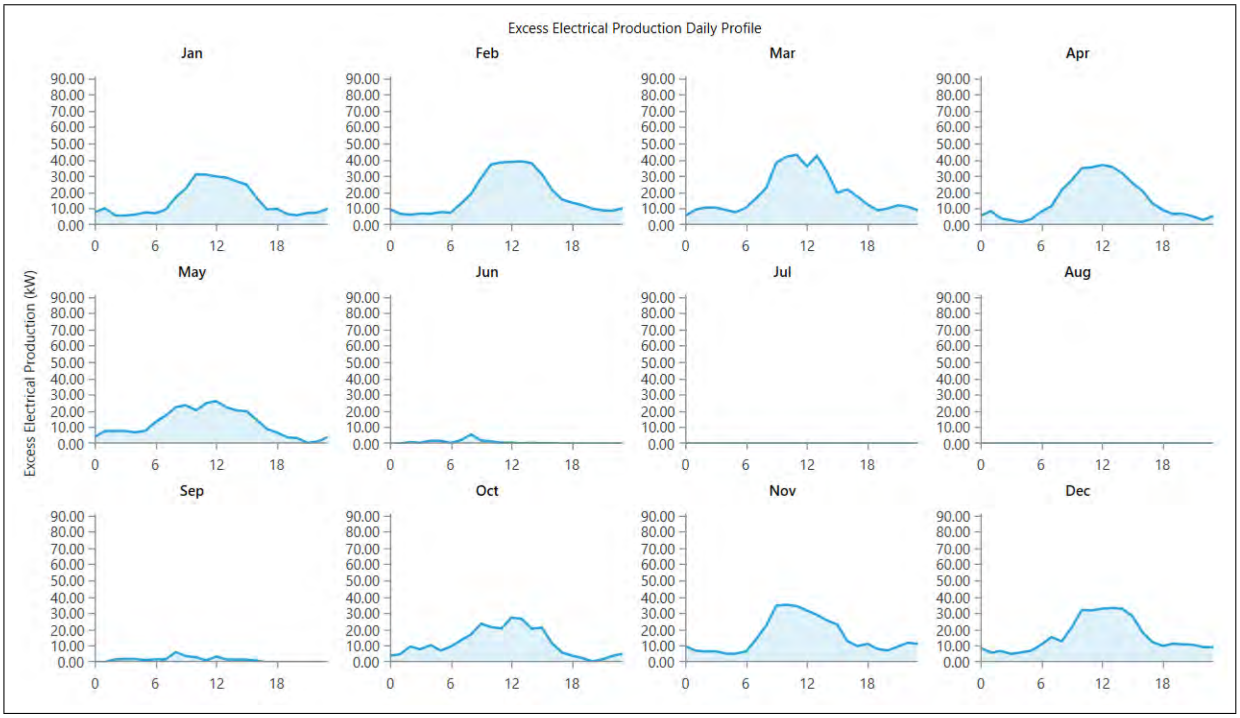

Figure 4.52: Excess Electrical Production Daily Profile Scenario 1.

Optimal configuration of Scenario 2 as mentioned earlier in Section 4.1 succeeds in eliminating Excess Electricity. Scenario 2 has a 0% of Excess Electricity in combination with a 51% of Renewable Fraction. The battery bank, the three conventional units and the RES (PV panels and Wind turbines) form the optimal configuration system in order to meet the load demands and eliminate the Excess Electricity percentage.

In Scenario 3 as it mentioned earlier the elimination of the Excess Electricity is impossible. The optimal configuration of the hybrid system occurred with respect the reduction of the Excess Electricity percentage. In Case 1 the battery units were chosen at 1260 batteries and the Excess Electricity of this case was 46.8% with a production of extra electricity of 1,241,700 kWh/yr. The intermittent and unpredictable nature of RES result in the over-production. The battery storage in relation with the production of the RES is considered inadequate to cover the demands of the Excess Electricity. The daily profile of the Excess Electricity of Case 1 of Scenario 3 can be seen in the Figure 4.53. Excess Electrical Production Monthly Averages are depicted in Figure 4.54. January, February, March, April, November and December are the months where Excess Electricity production occurs.

Case 2 of Scenario 3 the battery units are 2112 which it means that there is more capacity for the storing of extra energy. The Excess Electricity percentage and production of this case is 41.8 % and 1,030,406 kWh/yr respectively. The larger number of battery units compared to Case 1 of Scenario 3 results in the reduction of Excess Electricity percentage (41.8% to 46.8%). The battery with the merit of greater capacity than Case 1 stores the extra energy producing from the RES (PV panels and Wind Turbines). However is not possible to store all the Excess Electricity because the cost of a greater capacity battery soares. The daily profile of the Excess Electricity of Case 1 of Scenario 3 is highlighted in the Figure 4.55.

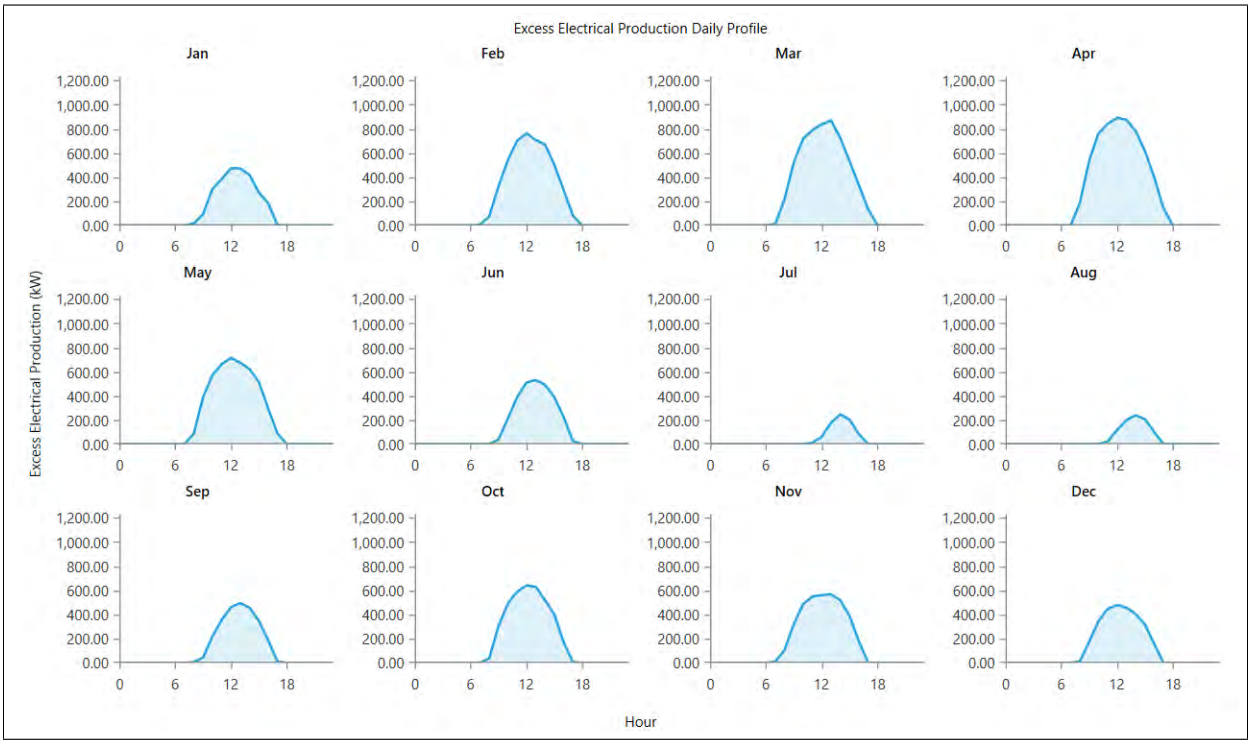

Figure 4.53: Excess Electrical Production Daily Profile Scenario 3 Case 1.

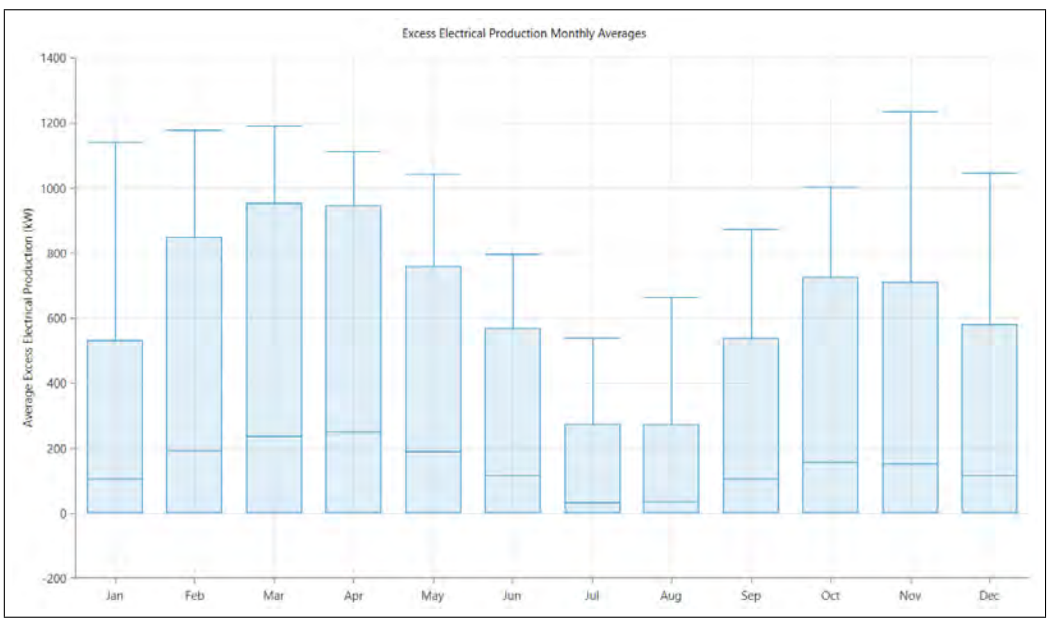

Figure 4.54: Excess Electrical Production Monthly Averages Scenario 3 Case 1.

Excess Electricity is not necessarily a sign of an inadequate and not feasible system design. In addition, sometimes it is more financially beneficial for a system not to invest huge amounts of money in storage technologies and include components that produce greater amounts of the electricity needed. Besides, there are some suggestions for the effective use

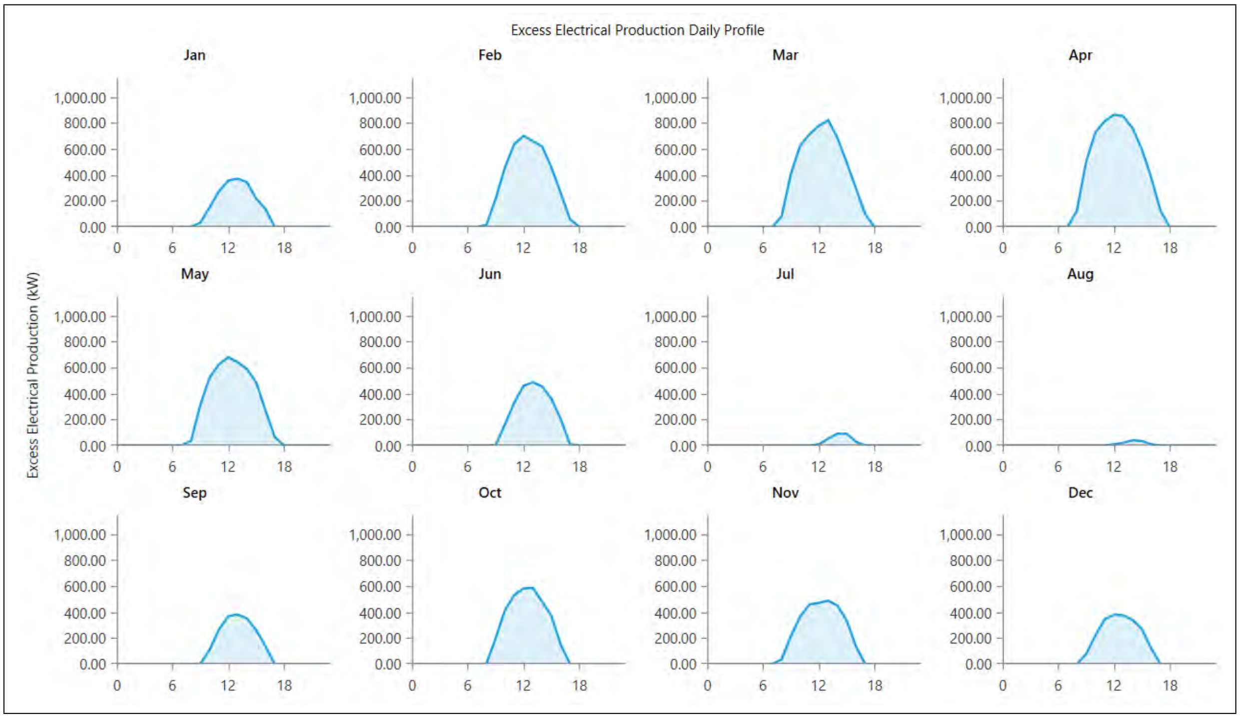

Figure 4.55: Excess Electrical Production Daily Profile Scenario 3 Case 2.

of the Excess Electricity. The extra energy that was produced in Scenario 1 and in cases of Scenario 3 could be useful for the island of Donoussa in many ways. Nowadays many Greek islands face water problems so one suggestion would be the usage of Excess Electricity for a desalination system (Reverse Osmosis). Moreover, in the future when Donoussa island is going to be connected with the rest power system of Greece, the Excess Electricity could be sold in the grid. Another proposition for the usage of extra energy would be the charging of electrical vehicles as the number of electrical vehicles increases and Donoussa is a tourist destination. So the future needs of electrical vehicles in the island of Donoussa could be meet through the Excess Electricity.

Chapter 5

Conclusions and Future Work

5.1 Conclusion

This thesis has been devoted to the optimal design of an autonomous hybrid system for the electrification of Donoussa island. Donoussa's load profile to seasonal fluctuation throughout a year due to the fact that island is a tourist destination during the summer months. As a result of this the energy demands from October to April the loads are limited, while the demands from May to September appear increased and a peak load occurs in August. The average monthly profiles for solar irradiation and wind speed were analyzed using HOMER software and as a result Donoussa island had great potential in the exploitation of solar and wind energy. Solar irradiation also varies throughout the year with a higher monthly average solar irradiation during summer months giving the PV panels the opportunity to be more efficient during summer months. The annual average radiation was 5.42 kWh/m^2/day. The island's wind speed was especially high during the year, making wind energy a favorable option for the production of energy. The average annual wind speed was measured at an altitude of 50 meters at 7.10 m/s.

Through this thesis was explored the possibility of the operation of a hybrid renewable energy system in Donoussa island which could supply the consumers reliably and would be less dependent on fossil fuels and on the conventional units of the island. Three main scenarios were implemented on this study with different renewable adoption rate (20%, 50% and 100%). Gradually conventional units of the existing power system were reduced in each scenario. Several techno-economical analyses were performed with the help of HOMER software. The optimal hybrid system for each scenario was chosen in respect to the minimum Excess Electricity percentage and the optimized NPC and LCoE. The main principle was the satisfaction of load all the time and the technical and economical feasibility of the hybrid system for a lifetime of 20 years.

After simulation and optimization, analysis revealed that the optimal system of Scenario 1 consisted of 5 conventional units of the existing power system (860 kW), 40 kW of Wind Turbines (2 units), 100 kW of PV panels and a converter of 80 kW. This configuration had 4.95 Millions € of NPC and 0.295 € of LCoE with a 6.68% of Excess Electricity. The optimal configuration of Scenario 2 consisted of 3 conventional units diesel generators (530 kW), 60 kW of Wind Turbines, 260 kW of PV panels, a 3,003 kWh storage system and a 200 kW converter. This system has no Excess Electricity percentage (0%), NPC is 4.03 Millions

€ and LCoE is 0.241 € with a renewable adoption rate of 51%. As for Scenario 3 (100% renewable system) two cases with a different capacity of energy storage were examined. The optimal hybrid system for the first case of Scenario 3 is composed of 70 kW of Wind Turbines (7 units), 1,450 kW of PV panels, 1260 battery units (9,009 kWh) and a converter of 470 kW. For Case 2 of Scenario 3 the optimal configuration consists of 20 kW of Wind Turbines, 1,450 of PV panels, 2112 battery units (15,100.8 kWh) and a 450 kW converter. The NPC and LCoE of the optimal configurations of the two cases of Scenario 3 are 3.76 Millions € and 0.224 € and 5.22 Millions € and 0.311 € . Case 1 of Scenario 3 has the lowest NPC and LCoE of all the scenarios. Cases 1 and 2 of Scenario 3 have the minimum percentage of Excess Electricity that is achievable in a 100% renewable hybrid system (46.8% and 41.8%). The results of this study the most feasible solution is optimal configuration of Scenario 2 which can cover the load demands. Optimal hybrid system of Case 1 with the lowest NPC and LCoE, shows that theoretically a 100% renewable system is feasible but in reality there are a lot of technical difficulties like voltage and frequency stability. A huge battery energy storage system has to be installed.

Sensitivity analysis was also performed in the three scenarios. Sensitivity analysis variables for Scenario 1 were three different values of diesel price, for Scenario 2 were three different values of diesel price and annual average wind speed and for Scenario 3 three annual average values of solar irradiation and wind speed. It is observed how the different factors affect the optimal system of each scenario. In Scenario 1 and 2 the NPC and LCoE are affected and in Scenario the Excess Electricity parameter is affected.

Finally, Donoussa island has great potential for the implementation of a hybrid system. The cost of a hybrid system is less than the existing power system and more environmental friendly. The NIIs are ideal areas for utilizing renewables in favor of local societies. Autonomous hybrid systems in remote areas like islands is a viable way of introducing green energy. Energy policies by governments should encourage and support actively this kind of power systems for the energy future of non-interconnected islands.

5.2 Suggestions for Future Work

The work and study that has been done in the framework of this thesis could be used as a base for diverse future work. In future a interconnection of Donoussa island power system to the electrical grid of mainland Greece is possible. A grid connected hybrid energy system could be examined. In addition, thermal energy load could be introduced in the energy simulation in order to be gained a broader perspective of remote islands. Hourly loads of different NIIs should be collected and similar studies for hybrid systems could be performed for the different NIIs in Greece. Common characteristics regarding loads, consumption and future construction of hybrid system could be highlighted as far as NIIs are concerned. Finally, a future study of a hybrid island in Donoussa could be done with most accurate cost data of renewable energy technology components and more sensitivity analysis case could be checked with the help of a high capacity computer.

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