Design and Techno-Economic analysis of a hybrid energy system for off-grid areas

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Χανιά, Οκτώβριος 2022

Abstract

In this thesis, a feasibility study for the design and optimization of an Energy system will be conducted. Hybrid Renewable Energy Systems (HRES) are an necessary option for the energy supply in distant places, such as in this case islands, where grid expansion is challenging. In this thesis, ten different scenarios will be examined, ranging from hybrid Power Stations with Low-Renewable energy(RES) source fractions and new generators to systems depending entirely on RES. The case study of the Dodecanese Island Symi, which is not presently linked to the grid, was chosen. This study's system will be sized depending on the year 2021. The system has a load of 14,218 MWh (peak load of 3,950 kW) and is not presently linked to the power grid of mainland Greece. The research will assume the project's lifespan to be around ten years, since Symi island is expected to be connected to the main grid by 2030 under IPTO plans. The optimization issue will consider Europe's present economic state, market pricing, and maintenance and operational costs. All parameters will be imported into HOMER PRO (student version with License Id: 180241), and each scenario will be evaluated based on the Net Present Cost (NPC), cost of energy, renewable fraction and minimum Excess Electricity %.

Abstract in Greek

Στην παρούσα διπλωματική εργασία θα εκπονηθεί μελέτη σκοπιμότητας για το σχεδιασμό και τη βελτιστοποίηση ενός Ενεργειακού συστήματος. Τα Υβριδικά Συστήματα Ανανεώσιμων Πηγών Ενέργειας (HRES) είναι μια απαραίτητη πλέον λύση για την παροχή ενέργειας σε απομακρυσμένα μέρη, όπως νησιά, όπου η επέκταση του δικτύου αποτελεί ιδιαίτερη πρόκληση. Σε αυτή την διπλωματική θα εξεταστούν δέκα διαφορετικά σενάρια, που κυμαίνονται από υβριδικούς σταθμούς ηλεκτροπαραγωγής με χαμηλή διείσδυση ΑΠΕ έως συστήματα που εξαρτώνται αποκλειστικά από ΑΠΕ. Σε αυτή την μελέτη θα εξεταστεί η περίπτωσης της Σύμης που ανήκει στο σύμπλεγμα των Δωδεκανήσων και επί του παρόντος δεν είναι συνδεδεμένη με το κύριο δίκτυο της χώρας. Το σύστημα αυτής της μελέτης θα έχει μέγεθος φορτίου με βάση το έτος 2021 και θα έχει φορτίο 14,218 MWh (αιχμή 3,950 kW). Η έρευνα θα θεωρήσει διάρκεια ζωής έργου ως δέκα χρόνια, αφού βάσει των σχεδίων του ΑΔΜΗΕ η Σύμη αναμένεται να συνδεθεί με το κεντρικό δίκτυο περίπου το 2030. Ο Σχεδιασμός και Τέχνο - οικονομική ανάλυση του ενεργειακού συστήματος θα γίνει στο πρόγραμμα HOMER PRO (φοιτητική έκδοση με Αναγνωριστικό άδειας: 180241) και θα λάβει υπόψη την τρέχουσα οικονομική κατάσταση της Ευρώπης, τις τιμές αγοράς και το κόστος συντήρησης και λειτουργίας. Το κάθε σενάριο θα αξιολογηθεί με βάση το Καθαρό Παρόν Κόστος (NPC) και την ελάχιστη πλεονάζουσα ηλεκτρική ενέργεια %.

Acknowledgement

I would like to express my deep gratitude to Dr. Spyros Papaeutuhimiou for being my thesis advisor and mentor. His constant support has helped me improve not only my academic knowledge but also helped me define my future career. Without his help and organization, this thesis would not be finished. Finally, I would like to show gratitude to my family and my friends for continuously supporting me to complete this thesis.

Table of Contents

Table of Contents

Chapter 1 : Introduction to the Thesis & its structure

Human development and economic growth are both linked to an adequate energy source. The evolution of energy production has accompanied human requirements based on their needs and has resulted in transitions from wood to coal in the 18^{th} century, to oil and gas in the late 19^{th} and 20^{th} century. Now a new energy transition from oil and gas to renewable energy sources is happening, with all members of the United Nations Framework Convention on Climate Change (UNFCCC) pushing for carbon neutrality and with the recent international tensions resulting the current energy prices to rise, renewable solutions seem to be the future, especially to off-grid locations with high energy costs and uncertainties due to volatile fuel prices. Building a reliable and self-sustainable system will make becoming independent from volatile energy imports easier while also helping reduce the human carbon footprint. Even though the energy transition is a big challenge on both the technical and societal systems, off-grid islands have even more difficult conditions that need to be tackled. A major hindrance is the economy, small energy production will not have the benefits of scale, resulting in cost savings that are gained with an increased energy production. Another drawback is the difference in seasonal energy loads, which may result in having excess electricity during low demand months due to an oversized system. Also the lack of infrastructure greatly reduces the optimal component choice while also increasing the installation costs. Currently most Greek Non-Interconnected Islands (NII) use diesel generators to cover demand loads while having a very small or a non-existing renewable penetration. The aim of this thesis is obtaining the most optimal solution for a Greek Non-Interconnected Islands. The case study of Symi island was selected.

1.1 Research Field

With all those factors in play a model of a microgrid must be created to obtain the best possible scenario for the selected island. The software HOMER(Hybrid Optimization of Multiple Energy Resources) has been chosen for the simulation of the different model scenarios. For the creation of the model, load data and the current installation for Symi island has been obtain by HEDNO (Hellenic Electricity Distribution Network Operator) The optimal model will be selected by the lowest Net-Present value, levelized energy cost

1.2 Thesis Structure

This thesis consists of the following chapters:

- In Chapter 1 Introduction & Thesis Structure
- In Chapter 2 the Current situation about Greek Non-Interconnected Islands is provided with some basic concepts and the law surrounding them, the case study of Symi is analysed.
- In Chapter 3, HOMER pro software is presented and how it is used.
- In Chapter 4, the development of the methodology is carried out with the modelling of components in order to insert them into HOMER pro.
- In Chapter 5, the optimization results obtained from the simulations of models in HOMER. Figures and costs are given for each method, where they are illustrated
- In Chapter 6, the conclusions of this work are summarized and listed and discussed

Chapter 2
2.1 Non-Interconnected Islands

"Non-Interconnected Islands" (NIIs) are considered those Greek islands whose Electricity Distribution Network is not connected to the Transmission System or the Distribution Network of the mainland. According to Article 130 of Law 4001/2011, HEDNO S.A. (the Greek DSO) is responsible for operating the Electrical Systems of the Non-Interconnected Islands, which includes operating the production, the market, and the systems of these islands. This operation is carried out in accordance with the "Operation Code of Electricity Systems of Non-Interconnected Islands".[1]

Energy right now for Non-Interconnected Islands is proving to be very expensive in both the environmental and economic sector. Right now the oil-fired plants, which mainly operate on the non-interconnected islands, participated in 2019 with a percentage of 10% in the produced energy. This results in petroleum products share reaching 1.3 million. Even though this percentage is low compared to many countries it must be noted that oil is only used to NNIs applications.

The Greek Independent Power Transmission Operator (IPTO) has planned investments of 4.3 billion Euros to gradually interconnect all country's islands to the mainland system. The company's plans have many phases each having each own deadline. At present IPTO is at the completion of the Cyclades Interconnection. The Cyclades interconnection project is split in four phases with three of them at present completed. Phase I entails the installation of the appropriate cables to link Syros with Lavrio, Paros, Mykonos, and Tinos.Phase II includes the connection of Paros with Naxos and Naxos with Mykonos. Phase III includes the second connection of Lavrio with Syros. Lastly Phase IV includes the connection with Santorini-Folegandros-Milos-Serifos and will mark the complete of this project.

According to RAE, the present situation of NIIs at present can be split into three main categories.

- Nineteen (19) "small" autonomous systems with a peak demand up to 10 MW.
- Eight (8) "medium-size" autonomous systems with a peak demand from 10 to 100 MW.
- Two (2) "large" autonomous systems with a peak demand of more than 100 MW (Crete and Rhodes).

The twenty-nine(29) systems will be present in the table below, some systems may consist of several islands.

	Autonomous systems	islands
1	AG.EFSTRATIOS	AG. EFSTRATIOS
2	AGATHONISI	AGATHONISI
3	AMORGOS	AMORGOS
4	ANAFI	ANAFI
5	ANTIKITHIRA	ANTIKITHIRA
6	ARKIOI	ARKIOI MARATHI
7	ASTIPALAIA	ASTIPALAIA
8	GAUDOS	GAUDOS
9	DONOUSA	DONOUSA
10	EREIKOUSA	EREIKOUSA
11	THIRA	THIRA THIRASIA
12	IKARIA	IKARIA
13	KARPATHOS	KARPATHOS KASOS
14	Crete	Crete
15	KITHNOS	KITHNOS
16	KOS-KALIMNOS	KOS PSERIMOS GIALI KALIMNOS LEROS LEIPSOI TELENDOS NISIROS TILOS
17	LESVOS	LESVOS MEGALONISI
18	LIMNOS	LIMNOS
19	MEGISTI	MEGISTI

20	MILOS	MILOS KIMOLOS
21	OTHONOI	OTHONOI
22	PATMOS	PATMOS
23	RODHES	RHODES HALKI
24	SAMOS	SAMOS FOURNOI THYMAINA
25	SERIFOS	SERIFOS
26	SIFNOS	SIFNOS
27	SKIROS	SKIROS
28	SYMI	SYMI
29	CHIOS	CHIOS OINOUSES PSARA

Table 1. Autonomous systems of NNIS, obtained from IPTO, DEDDIE.GR[2]

2.2 Greek Inter-connection plans

Figure 1: Map of the Interconnected Hellenic Transmission System(HETS). Projects in progress are noted in grey lines.[3]

IPTO's development strategy for future projects until 2030 includes the Dodecanese islands. For the electrification of the Dodecanese islands which include Kos–Kalymnos complex, Rodos, and Karpathos are to be interconnected directly to the Hellenic Electricity Transmission System (HETS) which is thought to be the optimal solution. the rest of the neighboring islands which include Symi, will be interconnected via MV cables to the nearest island substation.[3] In this way, a direct, solid, and cheap way of supplying electricity is created, allowing the greater penetration of RES with minor loses. Two interconnection scenarios of the Dodecanese islands exist. The first scenario is interconnection with the mainland system will be done through submarine cable connections to the continental grid through the Corinthian Substation. In this case the connection point in the Dodecanese, Kos is suggested as the closest connection point to ESMIE. The second scenario investigated by IPTO is A high-voltage, direct current (HVDC) interconnector from Peloponnese to Kos combined with HVAC 150 kV subsea interconnection branches to the system as well as between the islands.[3]

The plan for Symi Interconnection to the closest substation is not yet finalized due to the difficulty in determining the Kos-Rhodos connection route because of the submarine hydrothermal activity in the area which may prevent the installation of cables, forcing another route to be chosen.

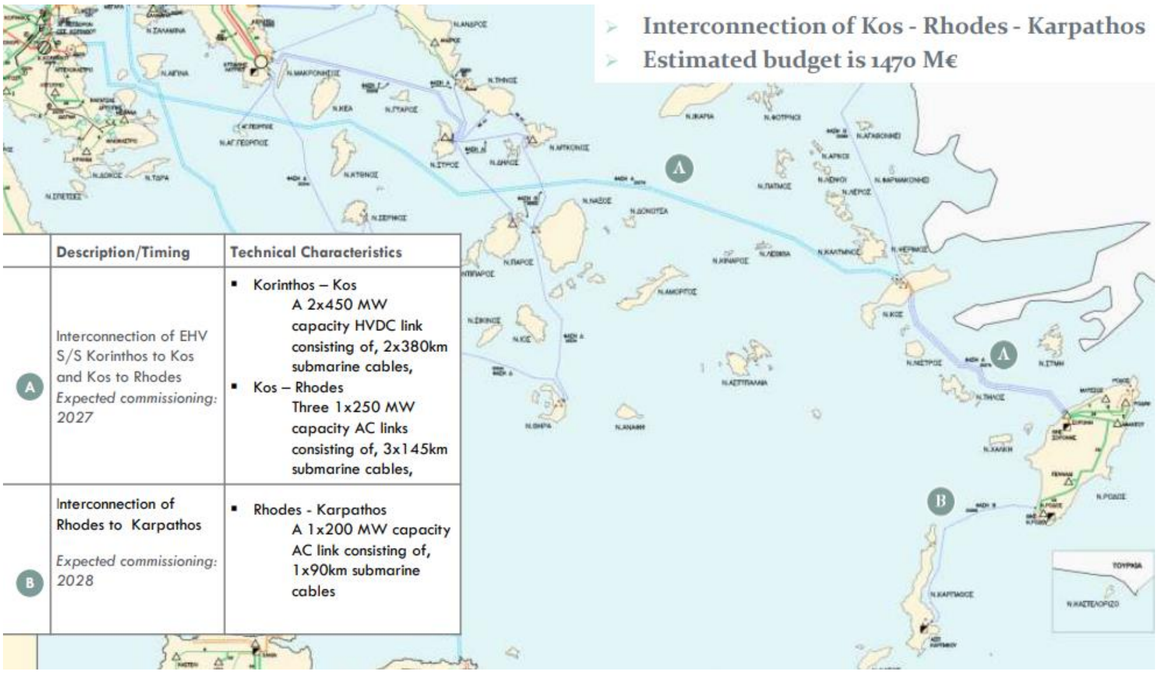


Figure 2. INTERCONNECTION OF THE DODECANESE ISLANDS[4]

Figure 3. Final map of the island interconnection projects. Projects that should be completed till 2024 are noted in red lines while project that span to the end of IPTO's ten year plan are noted in green lines. [2]

2.3 The Island of Symi

Symi is a small island in the Dodecanese Island chain, about forty-one kilometers north-west of Rhodes. It has a square area of 58,1 kilometers of mainly mountainous terrain. Symi is effectively waterless, and according to ELSTAT (2011) has a population of 2.590 permanent residents. Symi's population is separated between two towns. The biggest percentage of the population lives in Symi "town," which is in effect two villages: Yialos, the area round the harbor, and Horio, the "village," the original settlement up the mountain, overlooking the harbor. Then there is Pedi, which is a small village some distance from "Symi" (Yialos/Horio) and its the village where the HPPC's (Hellenic Public Power Corporation) facilities are located. Symi's installed power capacity is 7.325 MW provided by eight thermal generators. Symi at present has 190 kW of photovoltaic solar panels installed for renewables sources with some hybrid stations in evaluation by the Regulatory Authority of Energy (RAE).

Figure 4. The Island of Symi. Google Earth

2.3.1 Symi's Power Station

Symi's Autonomous Power Station which is located in Pedi consists of 8 diesel powered generators and have a total 7.325 MW power capacity:

Diesel Generators	NOMINAL POWER(MW)	TECHNICAL MINIMUM(MW)	FUEL	Consumption at 50% g/kwh	Consumption at 75% g/kwh	Consumption at 100% g/kwh
G1 (MITSUBISHI S16R-PTA)	1,275	0,600	Diesel	282,5	242,0	228,6
G2 (CEGIELSKI 6AL20/24)	0,550	0,290	Diesel	261,8	259,1	258,8
G3 (CEGIELSKI 6AL20/24)	0,550	0,290	Diesel	261,8	259,1	258,8
G4 (MITSUBISHI S16R-PTA)	1,275	0,600	Diesel	282,5	242,0	228,6
G5 (MITSUBISHI S16R-PTA)	1,275	0,600	Diesel	282,5	242,0	228,6
G6 (MTU 12V 4000G60)	1,205	0,616	Diesel	245,7	231,5	228,9
G7 (MTU 12V 4000G60)	1,205	0,616	Diesel	245,7	231,5	228,9
G8 (MITSUBISHI S16R-PTA)	1,205	0,600	Diesel	282,5	242,0	228,6

Table 2. Diesel Generators currently installed in Symi

Symi currently also has a total installation of 190 kW of Solar Photovltaic Arrays. In this way a hybrid energy system(HRES) is created. Hybrid Renewable Energy Systems (HRES) combine conventional energy sources with than one renewable energy sources, which work in standalone or grid connected modes. Based on the current legislation a HRE system is described as followed:

Hybrid Station: Any power generating station that:

a) Uses at least one form of Renewable Energy Source.
b) The total energy a HRES absorbs from the Grid, on an annual basis, does not exceed 30% of the total energy consumed to fill the storage system of this station. The energy absorbed by the Hybrid Station from the Grid, according to the previous paragraph, is defined as the difference between the energy measured when it enters the station and the energy directly attributed to the Grid by the RES units. of the Hybrid Station. This difference is calculated, for the Non-Interconnected Islands, on an hourly basis. If a technology other than that of photovoltaics is used for the utilization of solar energy, conventional energy that is not absorbed into the Grid may also be used, as long as the use of this energy is deemed necessary for the utilization of solar energy. The conventional energy used cannot exceed 10% of the total energy produced, on an annual basis, by the solar energy utilization units.

Based on the above legislation since Symi is not connected to the Hellenic Transmission System its installation is already considered a Hyrbid energy station since it has 190 kW of Solar Photovltaic Arrays.

As of 2022 Symi has four rejected projects of Hybrid Energy stations, two rejected projects for Photovltaic Arrays, five rejected projects for wind turbines and lastly nine Hybrid Energy stations projects still under consideration by RAE.

Figure 5. The Island of Symi. Red areas represent the rejected projects while yellow areas represent projects still under consideration. Provided by are geo.rae.gr [5]

From the above Diesel Generators presented in table 1, generator G2 and G3 of the CEGIELSKI 6AL20/24 type are out of operation due to maintenance problems and they are not expected to be repaired till the end of their service. It shall also be noted that generators MITSUBISHI S16R-PTA and MTU 12V 4000G60 operate at 0,9 MW and 0,7 MW respectively.

Model	MTU 12V 4000G60
Power Output	1600 kWe
Engine Speed	1500 rpm
Fuel Consumption for 100 - 75 - 50 % Of the load	381 - 296 - 174
AC Generator	-
Type	Brushless, 4 Poles
Number of phases	3
Frequency	50 hz
Voltage	380/220 V

Table 3. Specifications for diesel Generator MTU 12V 4000G60[6]

Model	S16R-PTA, V – Type 16 X, Turbo
Power Output	1520/1900 kWe/kVA
Engine Speed	1500 rpm
Fuel Consumption for 100 - 75 - 50 % Of the load	353 - 266 - 188 lt/h
AC Generator	Leroy Somer LSA512S55
Type	Brushless, 4 Poles
Number of phases	3
Frequency	50 hz
Voltage	415/240 - 400/230 - 380/220 V

Table 4. Specifications for diesel Generator S16R-PTA[7]

2.3.2 Symi Yearly Load

The data for Symi load are extracted from DEDDIE data publications and include the projected hourly time series of electricity demand for the year 2021. The time series was translated to a .dmd file and imported into HOMER Pro. HOMER automatically extracts island load statistics and charts observed below. The total demand for the year 2021 is 14,235 MWh. Average demand is 1623 kW, or 38.954,83 kWh/day and the peak demand is 3950 kW and is shown in mid-August. From diagram 8.1 particularly important conclusions can be made about the distribution emerge of the load. It is noticed that the demand of Symi is goes up during summer, with a large increase in load during the months of July, August and September and minor changes for the remaining months. More specifically, the average monthly load ranges from 1150 – 1450 kW outside from the months of July, August and September which are 2363, 2983 and 2041 kW, respectively. A similar behavior is observed for the monthly daily loads average of maximums where in August and July they are 2774 and 3437 kW respectively, 2436 kW for September while for the rest of the year it varies between 1800 – 2200 kW. Peak load is 3000 kW in August, 2600 kW in July, 2100 kW in September and 1900 kW in April, while for the rest of the year it varies between 1300 -1700 kW. Finally, the average minimum monthly loads range between 750-850 kW during winter and spring months but during summer average minimum loads range from 900 kW in June to 1805 kW in july and 2384 kW in August. During Fall September still averages 1533 kW minimum load with the rest months averaging between 823-1084 kW.

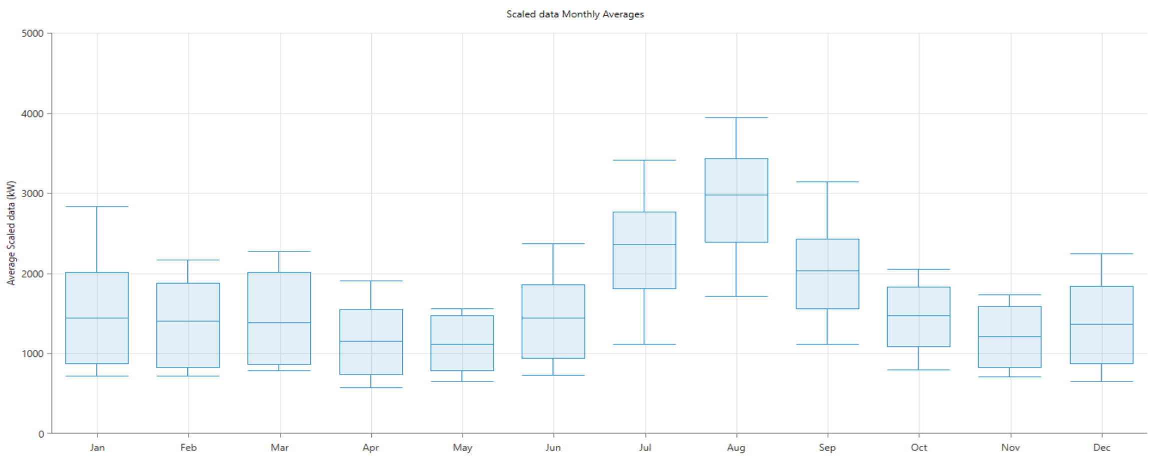


Figure 6. Monthly Average Load

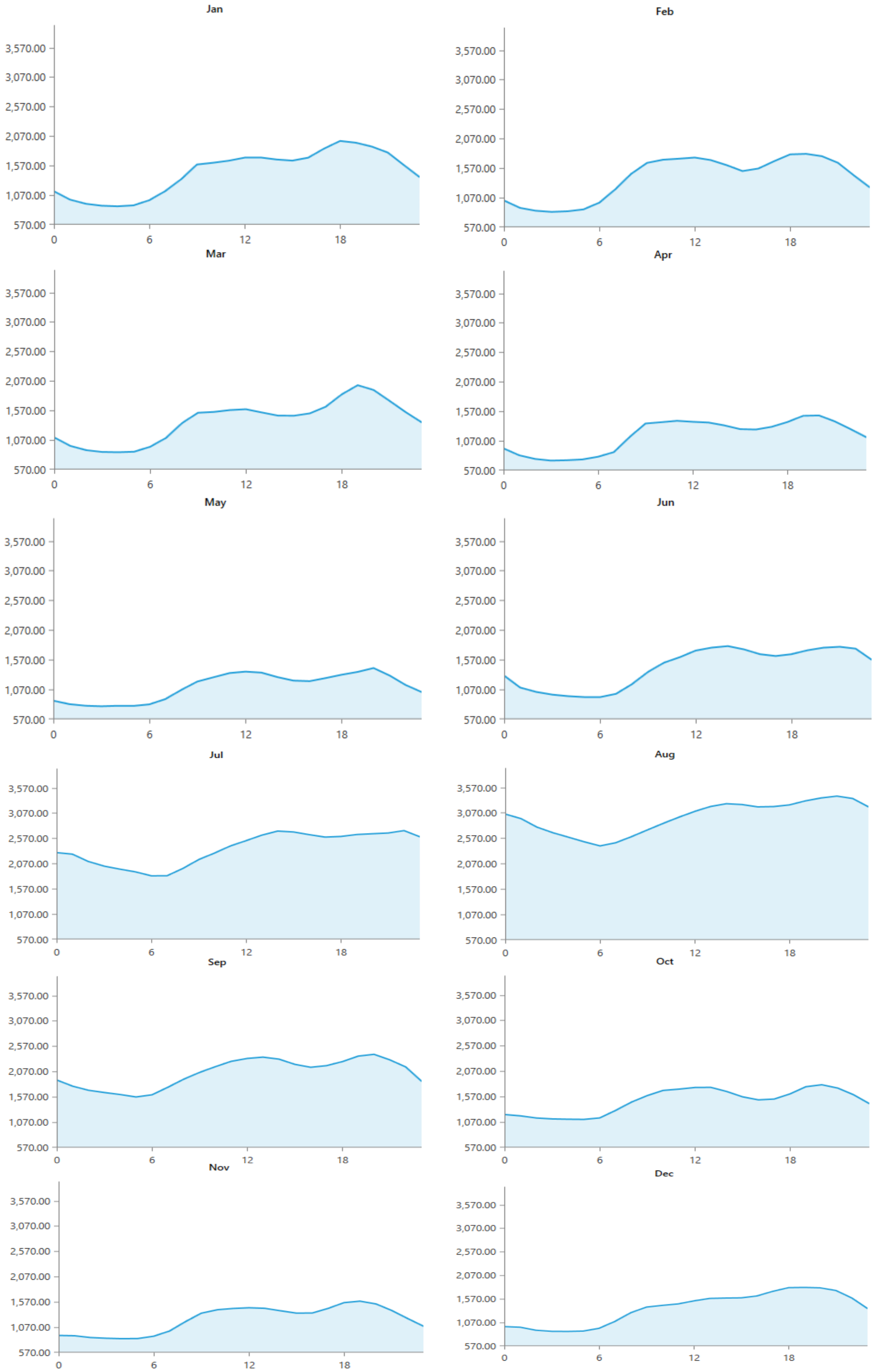


Figure 7. Daily Load Profile

As it is observed from diagram 3, the daily load distribution shows large changes during the duration of a twenty-four hour period, which although the load may differ in magnitude between months, the shape of the curve is pretty similar throughout the year. More specifically all diagrams show two global and two local extremes. Maximum load is observed around 9 pm for peak season months months and around 7 pm in the afternoon for the rest. The average values of the load in total maximum is 2100 kW in July, 2700 kW in August, 1600 kW in September and for the rest of the months it ranges at 1300 kW. Minimum load is observed at around 6 am for the peak season months and around 4 am for the off season months. The load value for the total minimums are 1000, 1300 and 800 kW respectively for the peak months (July, August, September) and the load varies around 700 kW for the rest months.A local maximum and minimum load is observed at 12 PM and 4 PM in the afternoon respectively.

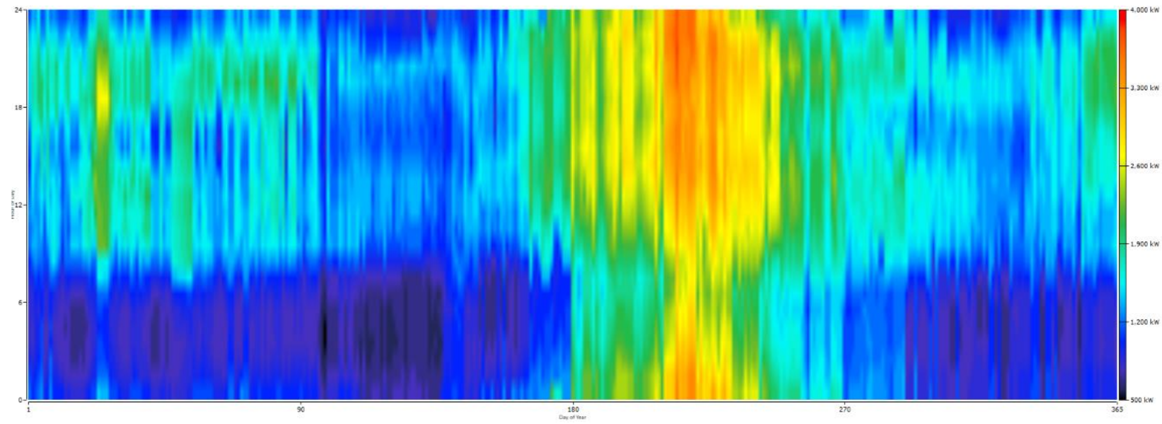


Figure 8. Daily Load throughout the Year

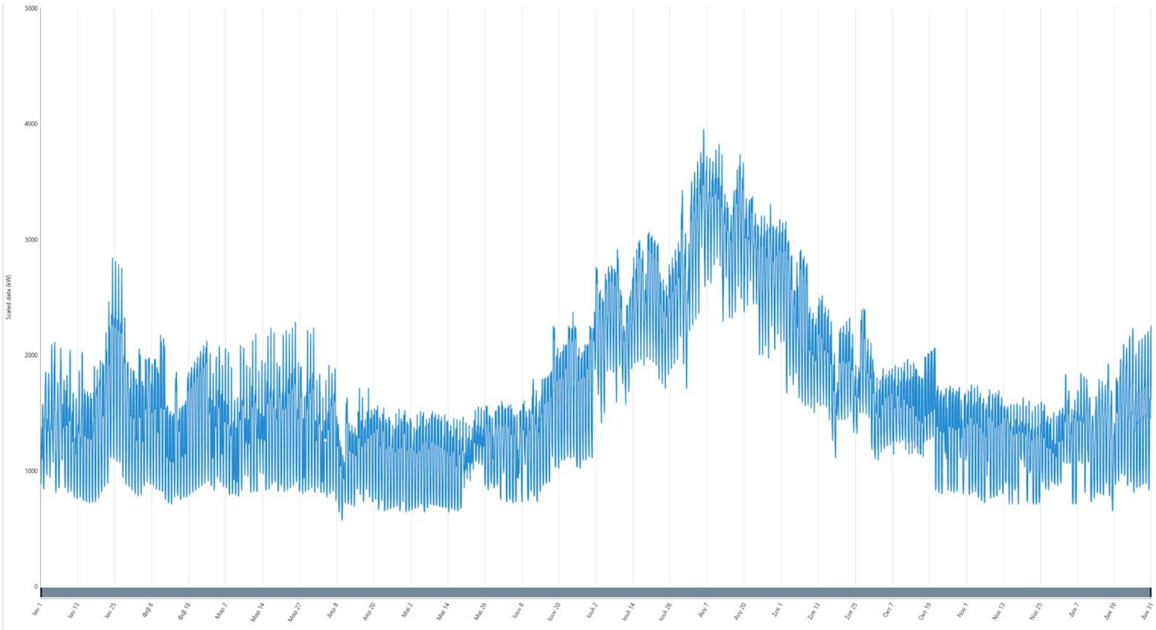


Figure 9. hourly Load throughout the Year

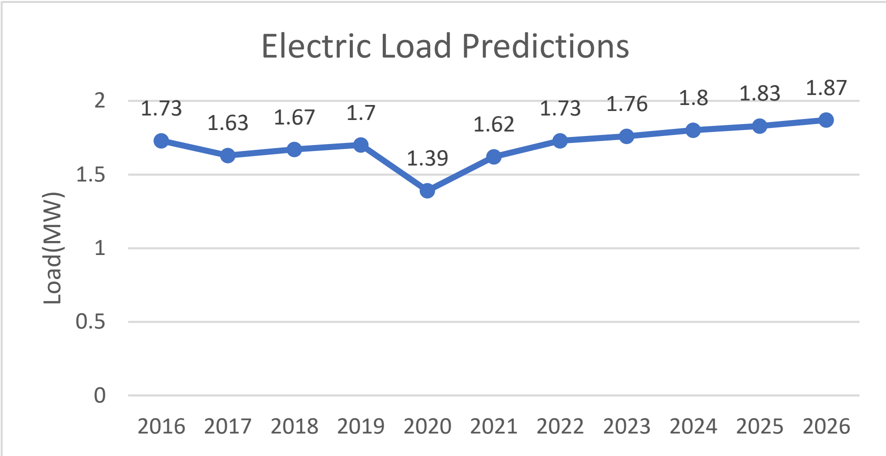
Analysis of past years loads and future predictions

Symi Past loads and predictions											
	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
Average Load (MW)	1,73	1,63	1,67	1,70	1,39	1.62	1,73	1,76	1,8	1,83	1.87
Peak Load (MW)	3,84	3,90	4,10	4,00	3,91	3.95	4,19	4,32	4,45	4,58	4,72
Load Factor (%)	45,1	41,7	40,9	42,5	35,5	0,41	0,41	0,41	0,40	0.39	0,40

Table 4. Prediction Table Source:Deddie

The load factor measures the difference between the amount of energy consumed over a certain period and the amount that would have been consumed if the power had been left on during a time of peak demand. It is a helpful indicator for outlining the patterns of electricity use over time. Facilities should try to avoid periods of elevated demand wherever possible. Facilities billed at greatest peak demand during the billing month.[8]

$$Load\ Factor(\%) = \frac{Average\ Load(MW)}{Peak\ Load(MW)}$$



Figuere 10. Fure Load Prediction Source:Deddie

Looking at Symi's current power installation and load profile and taking into consideration that Symi will not be connected to the Hellenic Transmission System(HETS) for at least 9-10 years installing renewable energy sources to the island and keeping the diesel generators to provide high load demands might prove more economical while also reducing CO2 emissions.

Chapter 3: HOMER Pro Simulation Software

3.1 Introduction to HOMER Pro

The Microenergy Optimization Model, or Homer program, was created by the National Renewable Energy Laboratory (NREL), Department of Energy of the United States. For this work an academic Student license was bought with license id: 180241 .

The HOMER software simulates a power generating system for a set period defined by the user and presents the results for the simulated years. The Homer software has simulation models for hydropower plants, wind turbines, solar modules, and conventional and alternative fuel generators. Models of various loads and alternate energy storage strategies are also included in Homer.

When necessary by its operator's electrical system, HOMER can simulate grid-connection, including predictive rules, and evaluate scenarios with and without a grid-connection. Homer permits the incorporating predictive rules as needed by its operator's electrical system and contrasting circumstances with and without a grid-connection. The user of Homer can determine the parts needed for a certain energy system. Additionally, the user provides a set of values for the optimization variables and the variables sensitivity . For each sensitivity input, Homer replicates the system, identifying the optimal combination of optimization variables running hundreds or thousands of simulations and comparing the results.

When setting up Homer, the first piece of information needed is the location of the area where the installation of the microgrid will be made. Having inserted the location, next some economic variables must be given by the user together with the duration of each project.

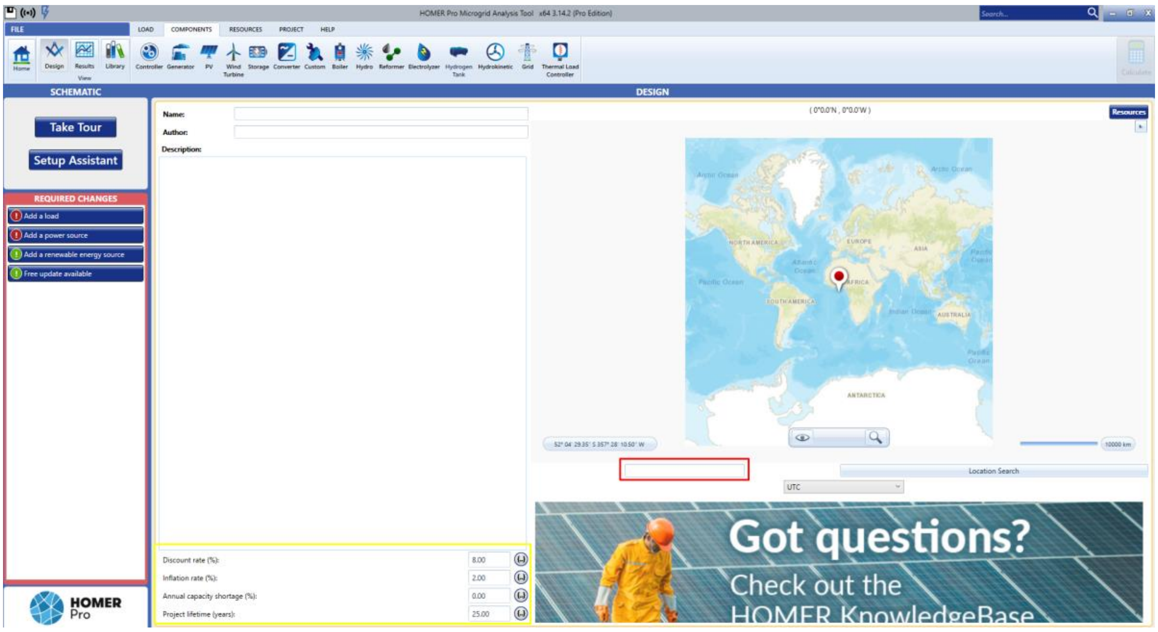


Figure 11. HOMER Pro home screen

Next the load must be imported into HOMER pro. By pressing the load icon in homer pro and selecting electric 1 the load page comes up. The months with the peak load must be selected and the load file must be imported. The load is a timeseries .dmd file which is 60 minutes interval for 365 days. The load value is represented in kw and was extracted from iptos monthly publications.

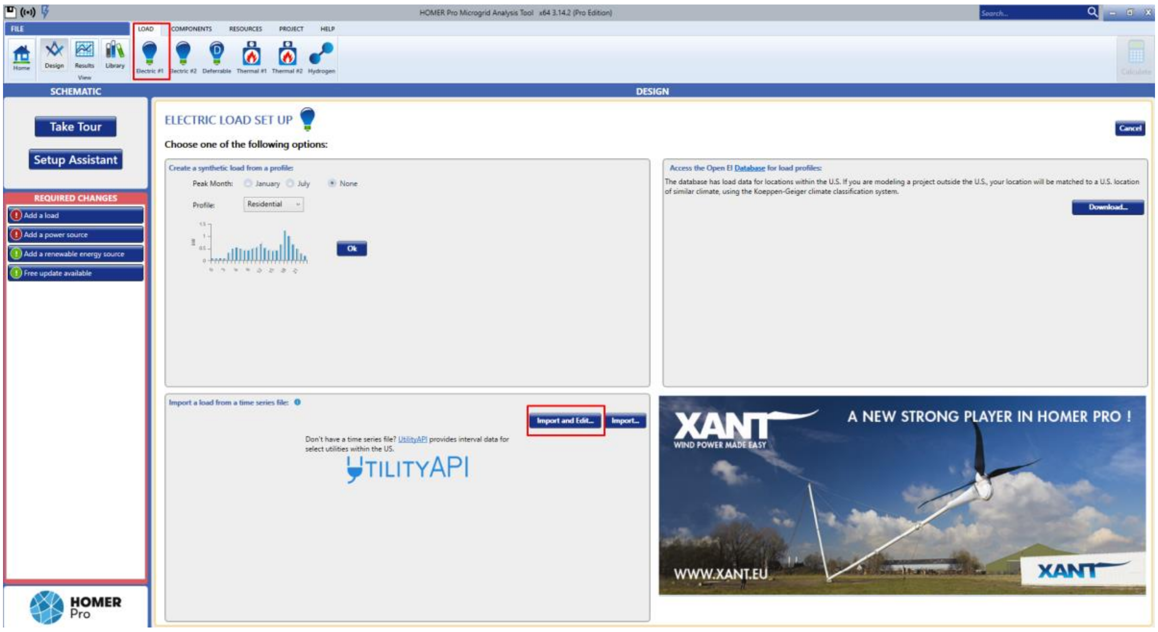


Figure 12. HOMER Pro Load screen

After importing those values into homer, homer will calculate daily kwh and the peak load. In this simulation case there is no thermal load.

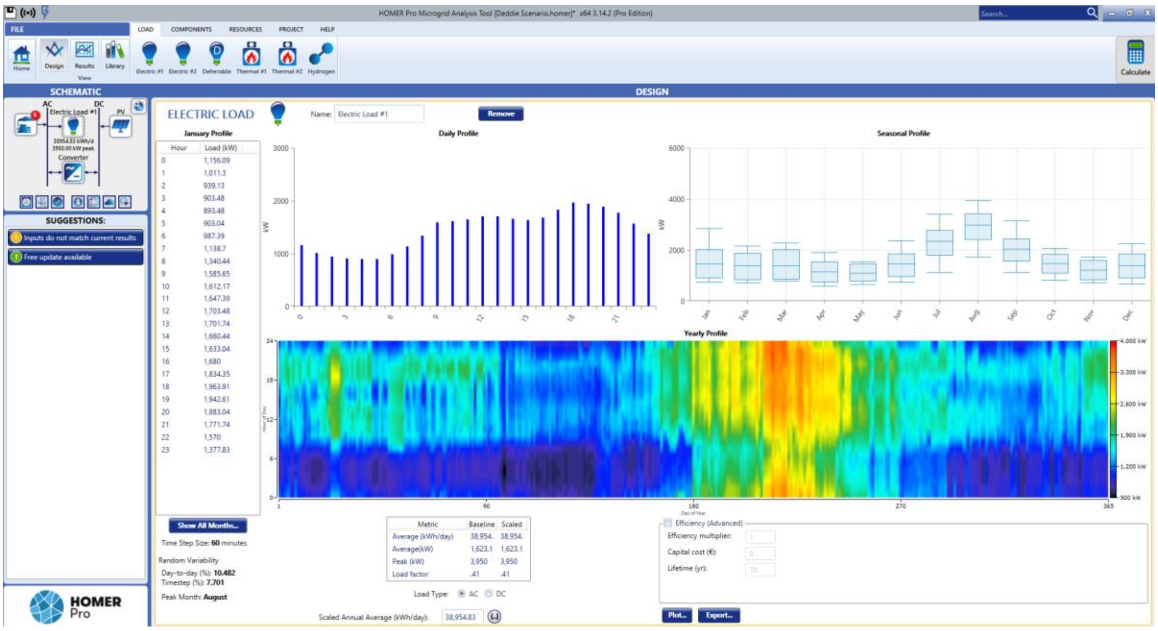


Figure 13. HOMER Pro Electric Load screen

After having imported the load the next section is components. In this section the components each scenario will have will be selected. Each component added to the system is represented by an icon on the right side of the program. Based on the type of load it produced it is either added on the AC bus or on the DC bus. Because the system in all simulation in this thesis will have both type of electric bus types a converter must be inserted to serve dc electricity to the load demand.

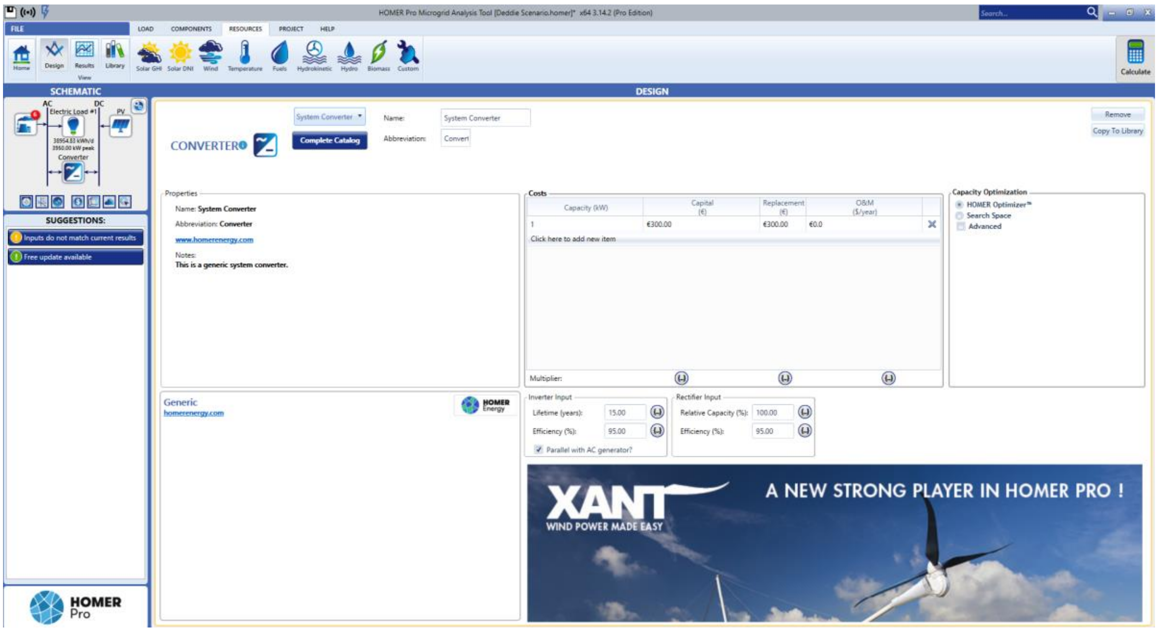


Figure 14. HOMER Pro Converter screen

Next going to the resources tab, the Global Horizontal Irradiance (GHI),Wind resource,temperature and fuel prices for the location selected will be downloaded and imported from NASA POWER [9]. For this case the location is Symi,Greece.

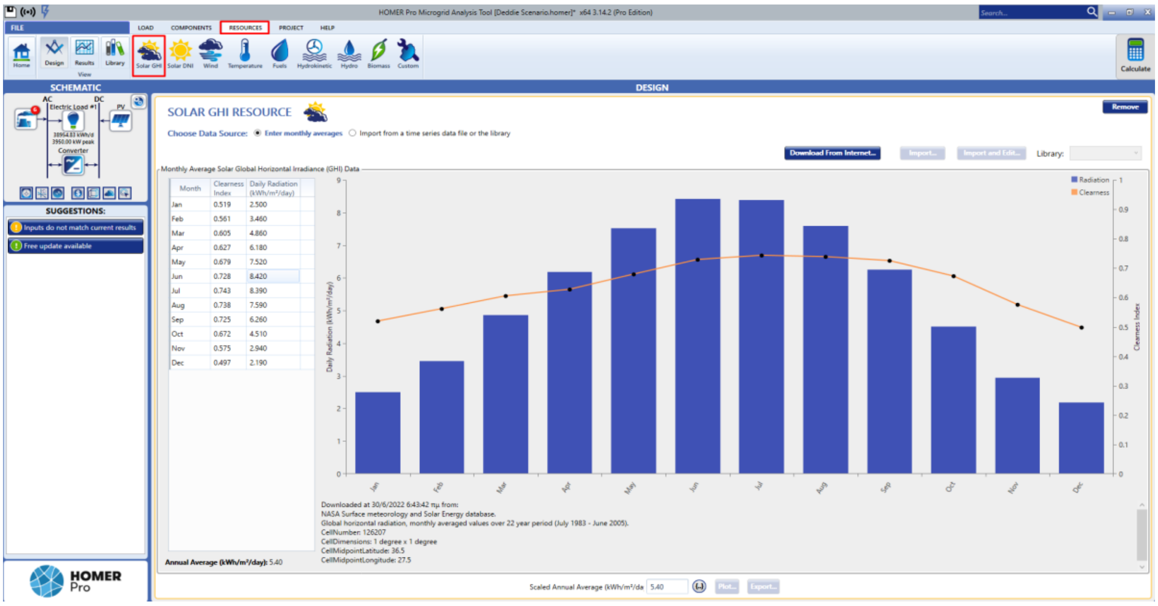


Figure 15. HOMER Pro Resources screen Global Horizontal irradiance

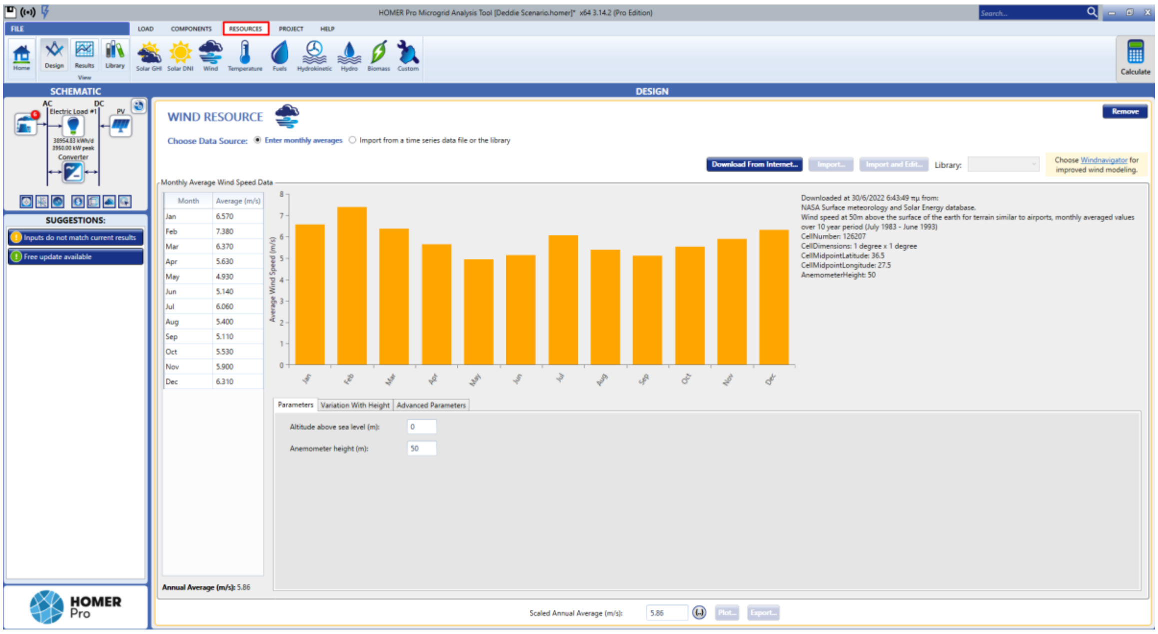


Figure 16. HOMER Pro Resources screen Wind Resource

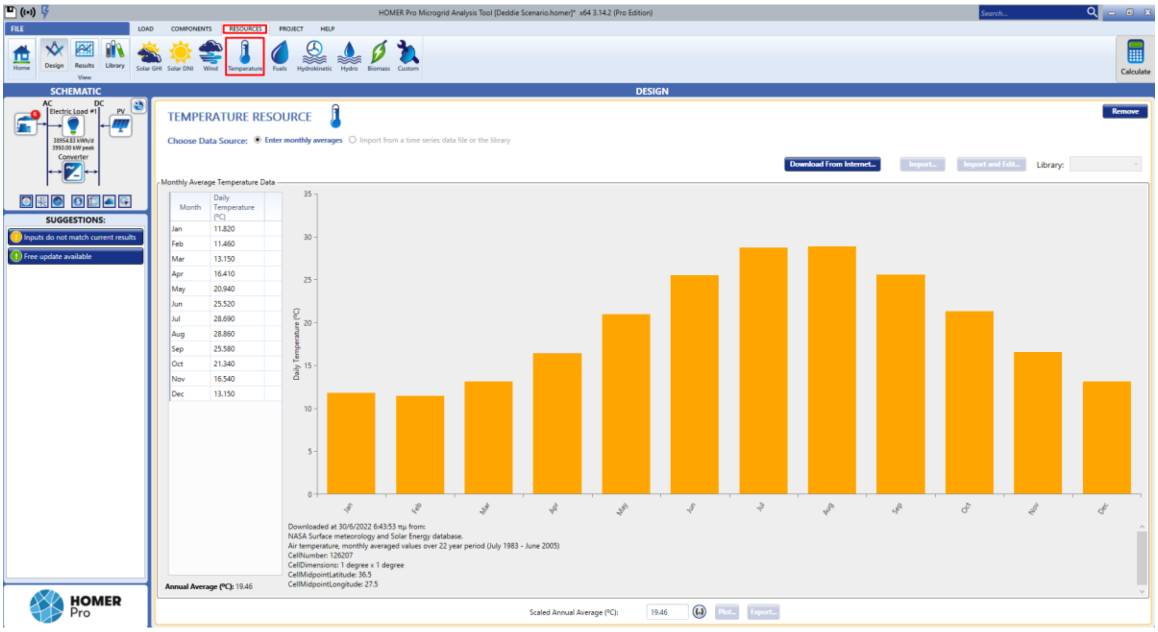


Figure 17. HOMER Pro Resources screen Temperature Resource

3.2 Resources assessment

The main components considered for the HRES are Diesel generators, solar photovoltaics(PVs) and wind turbines. Batteries will be used in different scenarios as back up facilities because of the intermittent nature of renewable natural resources and the big load variation during the day which leads to a duck curve[10] . To analyse the effectiveness of the solar and wind energy sources, solar radiation, wind speed and temperature have to be taken into consideration for the simulations. The data is taken from NASA Surface Meteorology through HOMER.

3.2.1 Solar Resource

The effectiveness of the solar panels will be determined by the global horizontal irradiation diagram. As HOMER states Global Horizontal Irradiance (GHI) is the total solar radiation incident on a horizontal surface. It is the sum of Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance, and ground-reflected radiation[11]. HOMER uses Solar GHI to compute flat-panel PV output.

The first and most important phase in the majority of PV power prediction systems is the prediction of the horizontal irradiance. Using statistical properties with historical GHI hourly data which is available, future values can be estimated[12]. The GHI dataset that will be used in the following simulations is from NASA (NASA's Surface Solar Energy Data Set) [9] and was automatically downloaded by HOMER based on coordinates of the island. The dataset include average values of 22 years(1983-2005). The average intensity of solar radiation is 5.40 kWh/m2/day and with average clearance of 0.639. In diagram 5 the daily GHI and clearance index are shown.

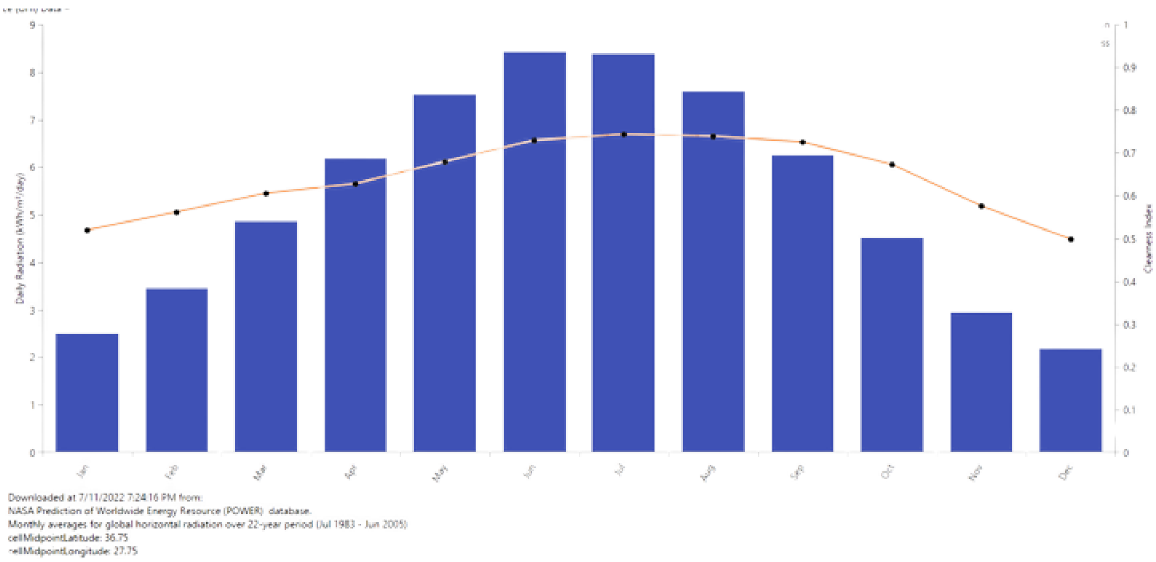


Figure 18. Monthly average Radiation data

3.2.2 Wind Resource

Wind resource is an important factor deciding the effectiveness of wind turbines. The timeseries wind speed dataset that will be used in the following simulations is from NASA [NASA Prediction of Worldwide Energy Resource(POWER) database][9]. From the data acquired, it is noticed that the annual average windspeed is 6.06 m/s for a height of 50 meters. The weibull parameter k is also important. The Weibull helps with the calculations of wind energy[13]. The wind speed and its distribution in a region variates from season to season. Nevertheless, the distribution of wind speed has very small variations from year to year. The changes in wind speed, over time of a year, are described by the Weibull frequency distribution.For the following simulations the weibull paramater k for symi will be k=1.6 and c=7.1 [14].

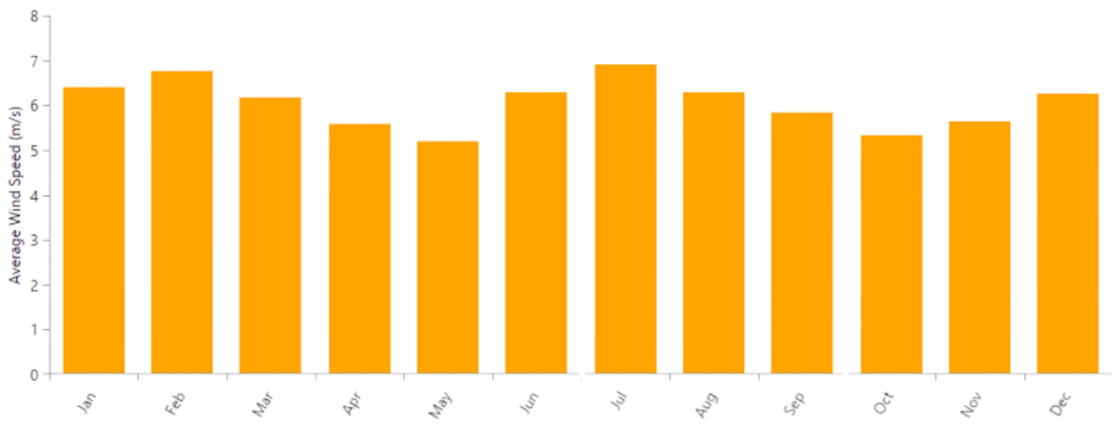


Figure 19. Monthly average Wind speed data

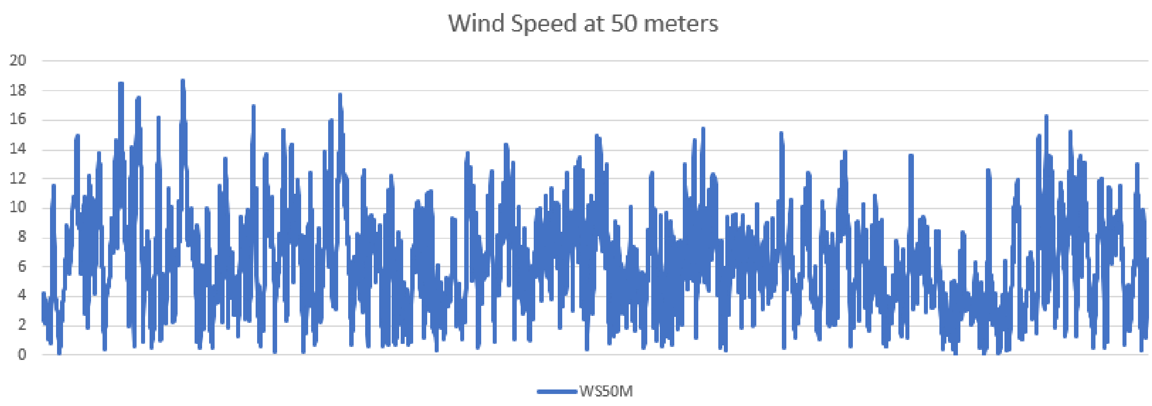


Figure 20. Hourly Wind speed data

3.2.3 Economic Parameters

At present, the energy problems in Europe combined with the previous problems created by pandemic have lead to massive changes in economy, resulting in increased discounts rates, inflation rates,fuel and component prices used by HRE systems. To successfully simulate and fine the most optized Hybrid Renewable energy system those variables that will determine the best possible scenario.

The first variable HOMER PRO needs to simulate a project is the nominal discount rate. Discount rate is the interest rate the banks borrow money and affect the interest rate of the loans that are issued, its rate is influenced by the state of the country's economy.. Current nominal discount rate for Greece is 3.8% for 2021 based on ELSTAT[15].

Next the current inflation rate is needed. Right now Greece is seeing an all time high inflation rate of 12.1%. Inflation is an increase in the level of prices of the goods and services. Typically, prices rise over time but right now the massive increase in fuel prices has inevitably cause huge price rises in all sectors.

Those two variables are used by HOMER PRO to calculate the real discount rate used to convert between one-time costs and annualized costs with the following equation:

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

Where i' is the nominal discount rate and *f* the inflation rate

HOMER PRO needs these variables to calculate the Net Present Cost(NPC). The NPC is the present value of all the costs of the installation and operation of the system during its lifetime without including the present value of the system and its earnings during its operation[16].

The NPC is another variable that HOMER PRO calculates that helps evaluating a system is Levelised Cost of Energy. This variable is calculated by dividing the annual cost of producing electricity by the total electriv load provided to the system

$$LCOE = \frac{Cann,tot - CboilerHserver}{Esystem,tot}$$

Where:

$C_{ann,tot}$ = total annualized cost of the system [€ /yr]
c_{boiler}= boiler marginal cost [€ /kWh]
H_{served}= total thermal load served [kWh/yr]
E_{served}= total electrical load served [kWh/yr]
In this specific case though no boiler exists so the LCOE equation is the following :

$$LCOE = \frac{Cann,tot}{Esystem,tot}$$

Component Modeling in HOMER PRO

3.3 Component Modeling in HOMER PRO

3.3.1 Solar PV Modeling :

Solar PV arrays in HOMER PRO are components that provide DC load into the system. HOMER PRO does not do deep modeling of solar PV arrays and uses standard values as inputs based on the general location of the system, the most important of these values are slope,azimuth and ground reflectance. The slope is the angle at which the panels are mounted relative to horizontal. A slope of 0° corresponds to horizontal, and 90° corresponds to vertical. With fixed-slope systems, a slope roughly equal to the latitude typically maximizes the annual PV energy production. The azimuth specifies the direction towards which the panels slope. The azimuth angle is the direction towards which the PV panels face. Due west is 90°, due north is 180°, and due south is 0°. Due east is -90°. The panels in fixed azimuth systems are virtually always pointed toward the equator.. Lastly ground reflectance (also called albedo) is the fraction of solar radiation incident on the ground that is reflected, HOMER uses a typical value of 20% for gras covered areas. HOMER PRO uses the following equation in deciding the power output of the PV panels:

$$Ppv = Ypv * fpv\left(\frac{\overline{G}_T}{\overline{G}_{T,STC}}\right)[1 + ap(Tc - Tc, stc]$$

Ypv = peak power output in kW,
fpv = derating factor of PV (%),
GT = solar radiation incident for a specific timeslot in kW/m2,
Gr,STC = standard test conditions incident radiation number (1 kW/m2),
ap = temperature coefficient (%/C),
TC = instant PV module temperature (◦C),
Tc,STC = standard test conditions PV module temperature (25 ◦C).

3.3.2 Wind Turbine Modelling

Wind energy is transformed into electricity by a wind turbine using the aerodynamic force of the rotor blades. As wind blows over one side of the blade, air pressure on that side of the blade decreases. The difference in air pressure on the blade's two sides causes both lift and drag. Because the force of the lift is higher than the force of the drag, the rotor spins. The rotor is attached to the generator. [17] Electricity is produced when aerodynamic force is converted to generator rotation. The equation states that W elec represents the yearly energy produced by wind turbines.

$$W_{elec} = \sum_{i=1}^{N_h} N_{tr} P_{tr}(V_t)$$

where t is the hour of the year, N_{tr} the number of turbines at the site, P_{tr} the power output as function of the average wind speed over a given hour, and Nh the number of data hour in the year The wind power output is given by the equation:

$$P_w = 0.5 \times n_t \times n_g \times p_a \times C_p \times A \times V_r^3$$

where: P = the mechanical power/kinetic power, Cp is the power coefficient which will be consindered 0.59 which is the theoretical maximum, ρ is the air density, A is the area swept by the wind, V the speed of the wind.From the Average hourly wind speed it is noticed that the wind rarely or never goes above 20 m/s. Selecting a wind turbine with higher cut off speed would ensure a continuous operation. For the islands average winds an ideal turbine would ideal be one with a big hub height and rotor. In that way the island would need only a few turbines to provide its load needs. Unfortunately the small harbor of the island does not have the capabilities to unload such turbines. For that reason two wind turbines will be taken into consideration. The XANT L-33 which is an easy transport, since it ships in a 40 feet container,easy installation wind turbine that provides 330 kW of power. The downside of XANT L-33 is their cost since a unit is appraised at around 1,020,000 € with installation . The second option that would be more of a challenge in terms of installation is a Vestas V82 which is 3,750,000€ for 1.6 MW[18]. The installation cost of the Vestas V82 will be considered 500,000/MW or 800,000€.[19] The operational and maintenance costs are 23,940 € for the XANT L-33 and 102,000€ for the Vestas V82[20].

Model	XANT L-33
Nominal Capacity (kW)	330 kW
Rotor Diameter (m)	33 m
Swept Area(m^2)	3,421.0 m^2
Cut-in/out wind speed (m/s)	3 m/S - 20.0 m/s
Hub/tower height (m)	55 m
Wind Turbine Cost (€)	1,020,000€
Replacement Cost (€)	1,020,000 €
Operation and Maintenance Cost (€/year)	23,940€

Table 5. XANT L-33 Specifications

Model	Vestas V82
Nominal Capacity (kW)	1,6 W
Rotor Diameter (m)	82.0 m
Swept Area(m^2)	5,281.0 m^2
Cut-in/out wind speed (m/s)	2.5 m/s / 32.0 m/s
Hub/tower height (m)	70 m
Wind Turbine Cost (€)	3,700,000 €
Installation Cost	800,000 €
Replacement Cost (€)	4,550,000 €
Operation and Maintenance Cost (€/year)	102,000€

Table 6. Vestas V82 Specifications

3.3.3 Batteries Modelling

Batteries can provide a reliable power supply and good power quality, while reducing the fluctuations from wind and solar energy. Peak demand periods may be used to sell power that has been stored, and switching from fossil fuel generators to storage reduces fuel use, emissions, and fines for emissions[21]. Among the batteries storage, this simulation will consider Lead-Acid batteries for their low cost but also Li-Ion batteries as due to the continuous develop-of technology and their increasing production and use have reduced significantly the installation costs as a result of which they have dominated the market. The most advantageous characteristic of Li-Ion batteries is their chargine time. Charging a lead-acid battery can take more than 10 hours, whereas lithium ion batteries can take from 3 hours to as little as a few minutes to charge, depending on the size of the battery. Lithium ion chemistries can accept a faster rate of current, charging quicker than batteries made with lead acid. For Lead-Acid batteries the model chosen is provided in the HOMER PRO library as Hoppecke 24 OPzS 3000 with the characteristics shown in the table below. It’s price from a local dealer is 1460 € per unit. One or more individual batteries are grouped together to form a battery bank. In this simulation, the battery system is represented by a single battery that can store a particular amount of DC current at a given round-trip energy efficiency. The batteries' state of charge point has been set at 80%.To calculate the required capacity the following equation is going to be used[22]:

$$C_{tot\_ah} = \frac{n_{day} * E_{load}}{n_b * DOD * V_b}$$

where nday is the number of days for which we consider the battery storage bank can offer autonomy to the system, if 5 days of autonomy is assumed, the system power supply availability can be larger than 95%[23] ,Eday_load is the average daily energy, hbat is the overall battery and inverter efficiency at , Vbat is the battery nominal voltage and DD is the allowable depth of discharge for the batteries. Depth of discharge (DoD) is a figure of merit used to indicate the state of charge of a battery . It is referred to as a charge removed from the battery at a specific state (Qd) in relation to the total charge that may be stored in this battery, and is typically stated as a percentage. For this computation, a lead-acid battery with 80% depth of discharge and a lithium-ion battery with 0% depth of discharge is deemed dead[24]. For n_{day}=1 day, E_{load}=38954.83 kWh, hbat= 86%, DOD= 70% and Vbat=2 VDC, the total required capacity for the batteries to solely power the system for a day for a day powered solely by batteries is $C_{tot\_ah} = 32{,}354.5$ or about 1348 kAH for an hour. Afterwards the total number of batteries is calculated using the following Equation[22]:

$$n_{battery} = \frac{C_{tot\_Ah}}{C_{single}} = \frac{32{,}353.8}{7.15} = 4{,}525`$$

where Csingle is the storage capacity for a single battery. The number of strings
is calculated by. As was previously established, a single bus has a voltage of 2 Volts, hence each string is going to contain 12 batteries (12 × 2 V = 24):

$$n_{string} = \frac{n_{battery}}{DC_{\_BUS}/V_b} = \frac{4{,}525.10}{48/2} = 188.54$$

Battery Model	Hoppecke 24 OPzS 3000
Battery Type	Lead-Acid
Nominal Voltage	2V
Nominal Capacity	7.15 kWh
Maximum Capacity(Ah)	3.57E+03
Rate Constant	1.24 1/hr
Efficiency	86%
Maximum Charge/Discharge Current	610 A
Unit Cost	1,460 €

Table 7. Hoppecke 24 OPzS 3000 Specifications

The same methology will be used to calculate the required Lithium-Ion batteries
For Lithium-Ion batteries the model chosen is provided in the HOMER PRO library as PowerPlus Energy LiFe4833 with the characteristics shown in the table below. It's price from a dealer is

2,359.00 € per unit. One or more separate batteries are grouped together to form the battery bank. The state of charge point for the batteries has been set at 100% in this simulation. The battery system is represented by a single battery, which is modeled as a device capable of storing a particular quantity of DC current at a specified round trip energy efficiency.To calculate the required capacity the following equation is going to be used[22]:

$$C_{tot\_ah} = \frac{n_{day} * E_{load}}{n_b * DOD * V_b}$$

For n_{day}=1 day, E_{load}=38954.83 kWh, hbat= 96%, DOD= 100% and Vbat=51.2 VDC, the total required capacity for the batteries to solely power the system for a day for a day powered solely by batteries is $C_{tot\_ah} = 792.53\ kAH$ or about 33.02 kAH for an hour. Afterwards the total number of batteries is calculated using the following Equation[22]:

$$n_{battery} = \frac{C_{tot\_Ah}}{C_{single}} = \frac{792.53}{3.28} = 241.625$$

The number of strings is calculated by:

$$n_{string} = \frac{n_{battery}}{DC_{\_BUS}/V_b} = \frac{241.625}{48/51.2} = 257.73$$

Battery Model	PowerPlus Energy LiFe4833
Battery Type	Lithium-Ion
Nominal Voltage	51.2 V
Nominal Capacity	3.28 kWh
Maximum Capacity(Ah)	64 Ah
Efficiency	96%
Maximum Charge Rate	0.9 A/Ah
Maximum Charge/Discharge Current	32/60
Unit Cost	2359 €

Table 8. PowerPlus Energy LiFe4833 Specifications

It is noticed that although Lithium-Ion batteries require a lot less total capacity because of their low single capacity the system will need a lot more compared to Lead-Acid. A simulation including both of these will be made to take advantage of the low cost of the Lead-Acid batteries and the perfomance of Lithium-Ion.

3.3.4 Natural Gas Generator

A natural gas generator, even though it is not a renewable energy source, it can provide reliable energy with minimal emissions compared to the already installed diesel generators. The natural gas generator is considered because providing energy during the transitional period between present and Symi's inteconnection may prove economically more viable than installing a lot of Renewable energy sources.
Natural gas has been regarded a transition fuel before renewable energy's technological feasibility can overcome its obstacles to generate secure and sustainable energy because it has approximately half the CO2 polluting effects of other fossil fuels.[25]

Normally natural gas would be a good investment due to the prices of natural gas. But at this point of time, natural gas prices have been the highest since the global crysis of 2008 with a price of around 7.9 USD/MMBtu [26] having more than doubled from the previous year of 2021. With the prices of natural gas and the initial capital needed to invest in the machines, the economic viability of Natural gas generators have to be test and simulated.

For this simulation a Caterpillar G3516C is chosen. The specifications of the generator are listed below.

Model	Caterpillar G3516H
Maximum Continuous Rating	2000 kW
Engine Speed	1500/1800 rpm
Fuel Consumption for 100 - 75 - 50 % Of the load	476 - 364 - 256 m^3/hr
AC Generator	Caterpillar SR5
Maximum Electrical Efficiency	37.70
Number of phases	3
Frequency	50 hz
Unit Cost	995,652 €
Operating Cost	0.018 kW [27]

Table 9. Caterpillar G3516C specification list. Provided by Caterpillar.[28]

These generators need natural gas to operate. Unlike diesel the island has no installation facilities to store and liquify natural gas. Because the required fuel average for the island is low, this thesis will use an ambient air Liquefied natural gas(LNG) regasification plant to store and regasify easily transported LNG tanks. The cost of this facility will be calculated at 12,000,000 €[29]. The initial capital of this investment will be added to the initial capital required to purchase the generator

Chapter 4: Scenario formulation and Simulation Results

In this chapter, the simulation and the techno-economic study will be carried out based on different scenarios. The simulations will be performed using the input parameters from the sections above . All system configurations that meet the load demand under the specified conditions of renewable resources were simulated in HOME PRO. At first the base scenario will include the present installation and calculate the theoretical costs of the base scenario. All the scenarios will have a project lifetime of ten years, since Symi should be connected to the main grid about that time. Based on these costs the comparison will be made between the different scenarios simulated.

4.1 Base Scenario

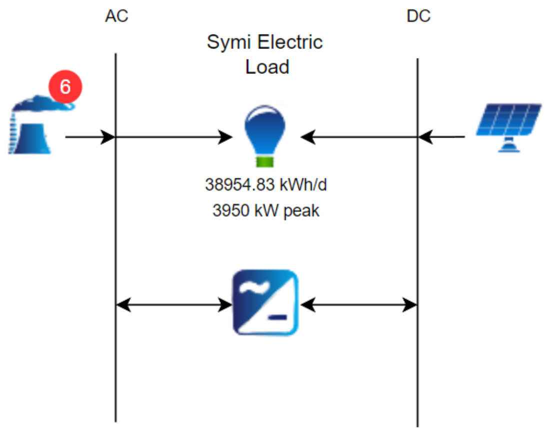


Figure 20. The base model used for simulation in HOMER

In the base scenario the installation includes the 6 Diesel generators mentioned above in figure 20 and 190 kW of PV arrays. The results HOMER pro produces for optimised electricity generation are shown in figure 21 below.

System	PV(kW)	S16R-PTA G1	S16R-PTA G2(kW)	MTU 12V 4000G60 (kW)	S16R-PTA G3(kW)	S16R-PTA G4(kW)	Converter (kW)	Excess Elec.(%)
Base Scenario	190	900	900	700	900	900	148	0

Table 10. HOMER Pro currect system Architecture

More specifically each component is presented in the table below:

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
MITSUBISHI S16R-PTA G1	7,530,457	52.9	860	1,738,633	8,760
MITSUBISHI S16R-PTA G2	4,508,316	31.7	552	1,044,078	8,174
MITSUBISHI S16R-PTA G3	1,472,002	10.3	427	341,754	3,451
MITSUBISHI S16R-PTA G3	351,261	2.47	318	81,859	1,105
MTU 12V 4000G60	36,925	0.259	178	9,835	208
MTU 12V 4000G60	-	0	-	-	-
Installed PVs	336,371	2.36	38.4	-	4,386
System		100			

Table 11 . HOMER PRO component details

From the results it is noticed that the largest percentage of the load is managed by the four Mitsubishi engines which in total have 21,490 operational Hours while the one MTU only works during peak load months.

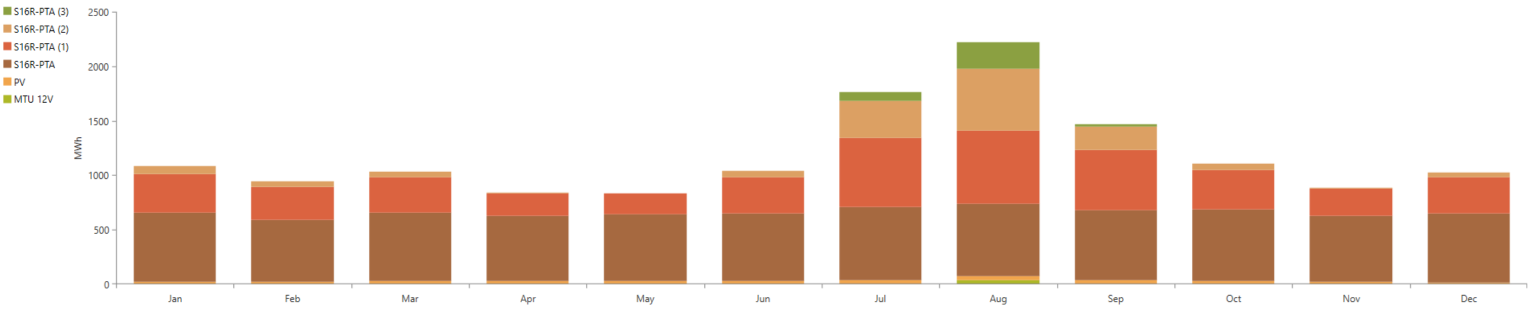


Figure 21. Monthly Electrical Production of base Scenario.

Unfortunately the current installation of PV arays is not enough to make any big difference to the system costs. Figure 9 and Table 10 depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 190 kW with a maximum power output of 167 kW.The total hours of operation of PV panels is 4386 h/year which is about 12 hours per day.

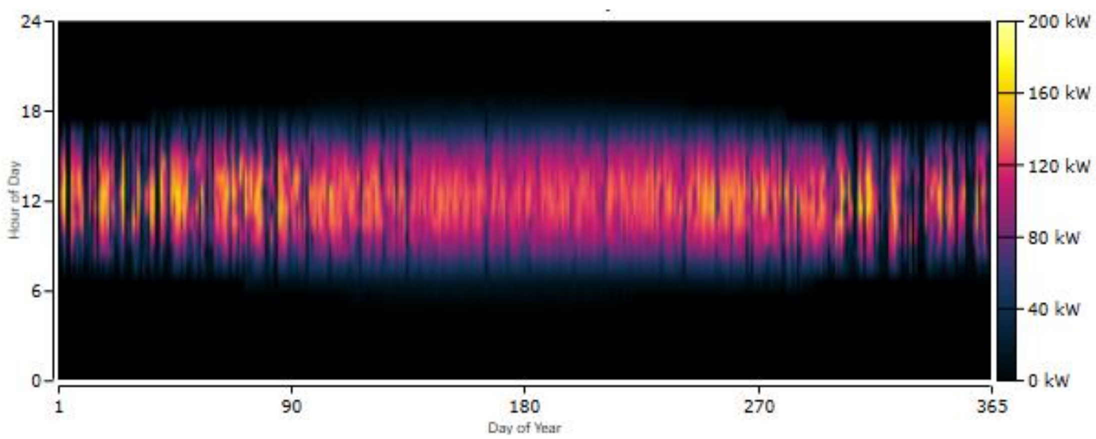


Figure 22 . Hourly PV Power Production of base Scenario.

HOMER PRO PV result table

Quantinty	Value	Units
Rated Capacity	190	kW
Mean Output	35.1	kW

Mean Output	842	kWh/d
Capacity Factor	18.5	%
Total Production	307,511	kWh/yr
Minimum Output	0	kW
Maximum Output	167	kW
PV Penetration	2.16	%
Hours of Operation	4,386	Hrs/yr
Levelized Cost	-0.0286	€/kWh

Table 12 . Base scenario PV result table

Following the system costs, the economic aspects for the base system are presented in Table #. It is noticed that the huge cost of the selected configuration is the fuel costs. The diesel costs the year 2022 have rosen massively which leads with this system have a fuel cost value of € 6,148,491.58€/year. This can be justified from the fact that diesel operate at 21,490 hours/year to satisfy the high load demand of the island. That is why the fuel consumption very high especially at seasonal months. The Initial Capital cost of the diesel generator units is considered 0 since they have been already installed and operating at the island for years.

Economic Characteristic of Symi Base Scenario:

Scenario	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(L/yr)
Base Scenario	€92,657,260	€0.4325	€6,128,224	€0.00	2.05%	3,222,480

Table 13 . Economic Results of base scenario

Detailed costs by each component are depicted in the next Table.

Component	Capital	Replacement	O&M	Fuel	Total
MITSUBISHI S16R-PTA	€0.00	€0.00	€0.00	€49,999,653.56	€49,999,653.56

MITSUBISHI S16R-PTA (1)	€0.00	€0.00	€0.00	€30,120,330.00	€30,120,330.00
MITSUBISHI S16R-PTA (2)	€0.00	€0.00	€0.00	€9,881,781.76	€9,881,781.76
MITSUBISHI S16R-PTA (3)	€0.00	€0.00	€0.00	€2,367,709.33	€2,367,709.33
Installed PVs	€266,000.00	€0.00	€48,673.20	€0.00	-€9,340.87
MTU 12V 4000G60	€0.00	€0.00	€0.00	€282,765.98	€282,765.98
Other	€0.00	€0.00	€10,186,795.18	€0.00	€10,186,795.18
System Converter	€44,445.00	€0.00	€0.00	€0.00	€14,368.13
System	€310,445.00	€0.00	€10,235,468.37	€92,652,240.64	€102,844,063.07

Table 14 . Detailed costs of base scenario

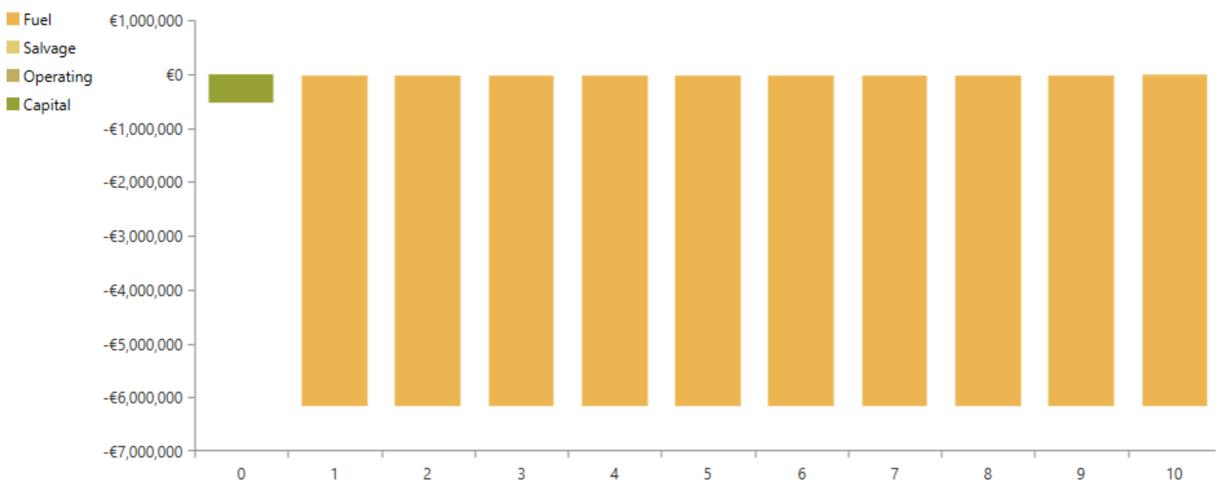


Figure 23. Cash flow by Cost type base Scenario .

4.2 Scenario 1

In scenario 1, the option of expanding the solar PV arrays while keeping the already installed diesel generators will be simulated. For this scenario the search space for PV arrays will be set at 1000-1200-1800-2500-3000-3200 kW, a figure which the island is capable to provide in space. There will be no changes in the diesel generators in order to provide load that can not be met with solar generation. The economics of the simulation remain the same as base scenario.

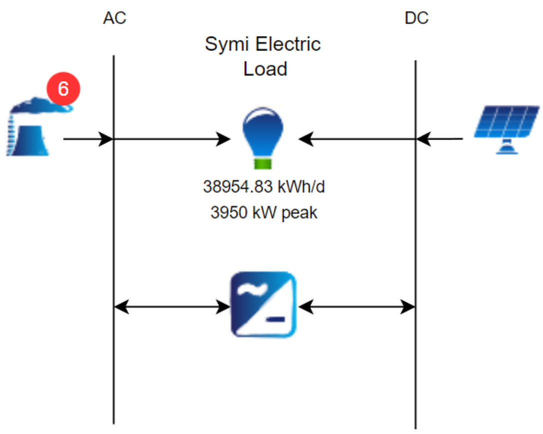


Figure 24 . Scenario 1 used for simulation in HOMER

The architecture result HOMER output are the shown in table 15. It is noted that in this case excess electricity production exists in the system. This is the result of non existing battery bank. The results of the excess electricity production compared to the load are show in figure 26.

System	PV(kW)	S16R-PTA G1	S16R-PTA G2(kW)	MTU 12V 4000G60 (kW)	MTU 12V 4000G60 (kW)	S16R-PTA G3(kW)	S16R-PTA G4(kW)	Converter (kW)	Excess Elec.(%)
Scenario 1	3,200	900	900	700	700	900	900	1,975	7.38

Table 15 . HOMER PRO Optimised Architecture for scenario 1

More specifically each component is presented in the table below :

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
MITSUBISHI S16R-PTA G1	5,772,440	36.7	659	1,334,974	8,760
MITSUBISHI S16R-PTA G2	3,375,755	21.5	419	783,900	8,054
MITSUBISHI S16R-PTA G3	1,072,217	6.82	359	249,453	2,987
MITSUBISHI S16R-PTA G3	284,367	1.81	302	66,323	943
MTU 12V 4000G60	27,300	0.174	177	8,170	154
MTU 12V 4000G60	175	0.00111	175	53	1
Installed PVs	5,179,126	33.0	591	-	4,386
System		100		2,442,873	

Table 16. HOMER PRO component details

From the results it is noticed that the largest percentage of the load is managed by the Mitsubishi engines G1, G2 and the installed PVs. The two MTU 12v 4000G60 engines have low hours with both operating at peak August time and with, one starting for only one hour per year . This can be avoided with a more relaxed annual capacity shortage.

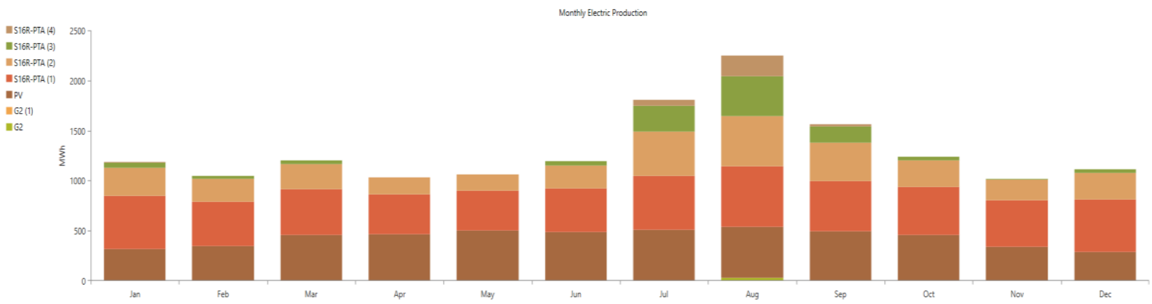


Figure 25. Monthly Electrical Production of Scenario 1.

The installation of PV arays has expanded a considerable amount from the previous scenario. In this case, it is to be expected that Photovoltaics will affect the system cost. Figure 26 and Table 17 depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 3200 kW with a maximum power output of 2,805 kW.The total hours of operation of PV panels remains the same, which is to be expected at 4386 h/year which is about 12 hours per day.

Quantity	Value	Units
Rated Capacity	3,200	kW
Mean Output	591	kW
Mean Output	14,189	kWh/d
Capacity Factor	18.5	%
Total Production	5,179,126	kWh/yr
Minimum Output	0	kW
Maximum Output	2,805	kW
PV Penetration	36.4	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0679	€/kWh

Table 17. Solar PV simulation Results of scenario 1

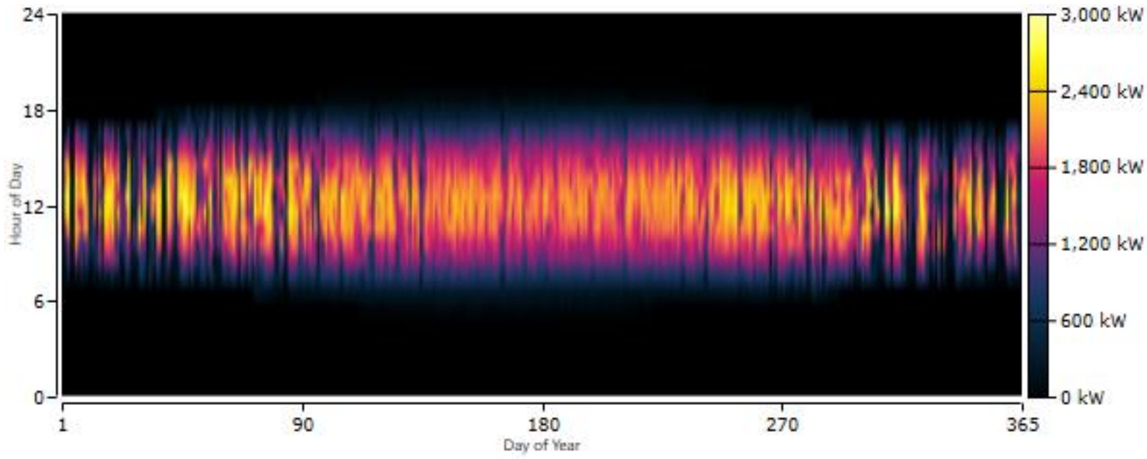


Figure 26. Hourly PV Power Production of Scenario 1.

From figure # it is noticed that besides peak load months the system producses excess electricity during the day. Because there is no storage system in this scenario the excess electricity is unable to be saved and used later, ending up as waste.

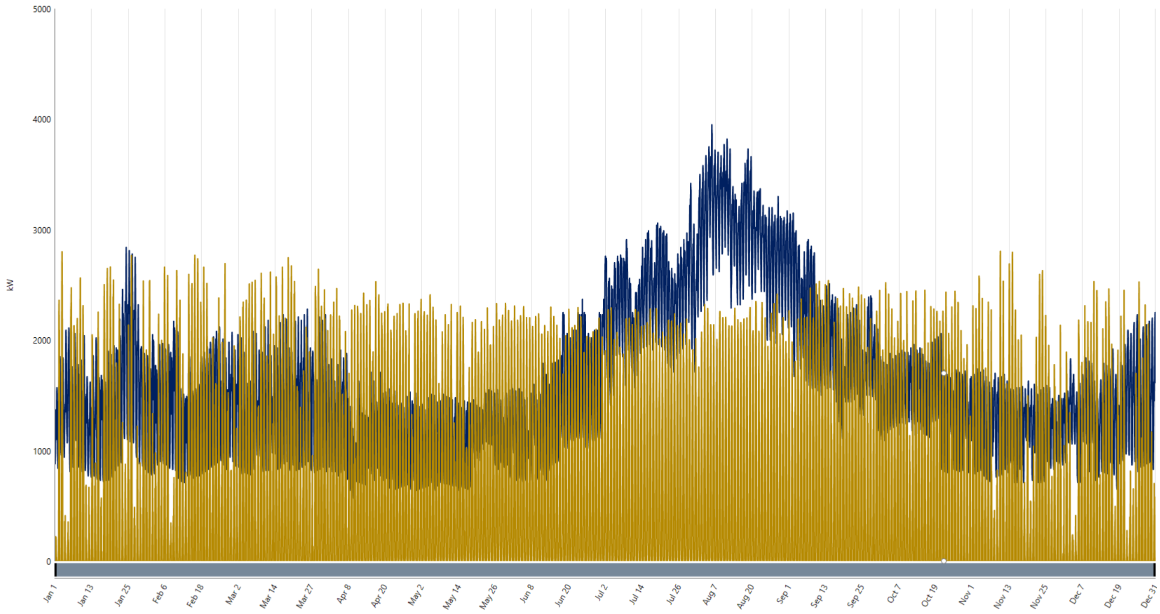


Figure 27 . Hourly PV Power Production and the load demand of the system in Scenario 1.

Following the system costs, the economic aspects for the base system are presented in Table #. As expected the huge cost of the selected configuration is the fuel costs since the diesel generator configuration has remained the same. The diesel costs the year 2022 have rosen massively which leads with this system have a fuel cost value of € 4,662,198.21 /year a decrease of 1,487,491.224 €/ year. It is noticed that even though there was a big incread in the PV arrays the operation hours of the diesel generators fell only by 592 hours, but the diesel costs fell aproximately 24.2 %.

Total fuel consumed	2,443,500	L
Avg. fuel per day	6,695	L/day
Avg. fuel per hour	279	L/hour

Table 18. Annual fuel consumed in scenario 1

Economic Characteristic of Scenario 1:

Scenario	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(L/yr)
Scenario 1	€83,871,810	€0.3914	€5,229,191	€5,072,600	26.9%	2,442,872

Table 19. Optimised System costs

Detailed Net present costs by each component are depicted in the next Table.

Component	Capital	Replacement	O&M	Fuel	Salvage	Total
MITSUBISHI S16R-PTA	€0.00	€0.00	€0.00	€38,382,965.94	€0.00	€38,382,965.94
MITSUBISHI S16R-PTA (1)	€0.00	€0.00	€0.00	€22,538,560.27	€0.00	€22,538,560.27
MITSUBISHI S16R-PTA (2)	€0.00	€0.00	€0.00	€7,172,222.33	€0.00	€7,172,222.33
MITSUBISHI	€0.00	€0.00	€0.00	€1,906,904.00	€0.00	€1,906,904.00

S16R-PTA (3)						
Installed PVs	€4,480,000.00	€0.00	€819,759.09	€0.00	-€5,457,079.04	-€157,319.95
MTU 12V 4000G60	€0.00	€0.00	€16,244.49	€234,914.11	-€382,563.98	€78,594.62
MTU 12V 4000G60 (1)	€0.00	€0.00	€105.48	€1,509.47	-€426,050.08	-€214,435.12
Other	€0.00	€0.00	€7,722,324.94	€0.00	€0.00	€7,722,324.94

Table 20. Analysis of System costs for scenario 1

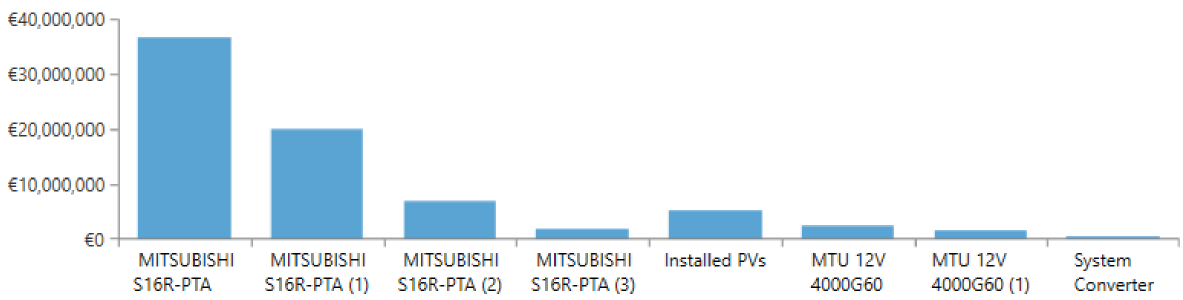


Figure 28. Net Present Cost Summary by component for Scenario 1.

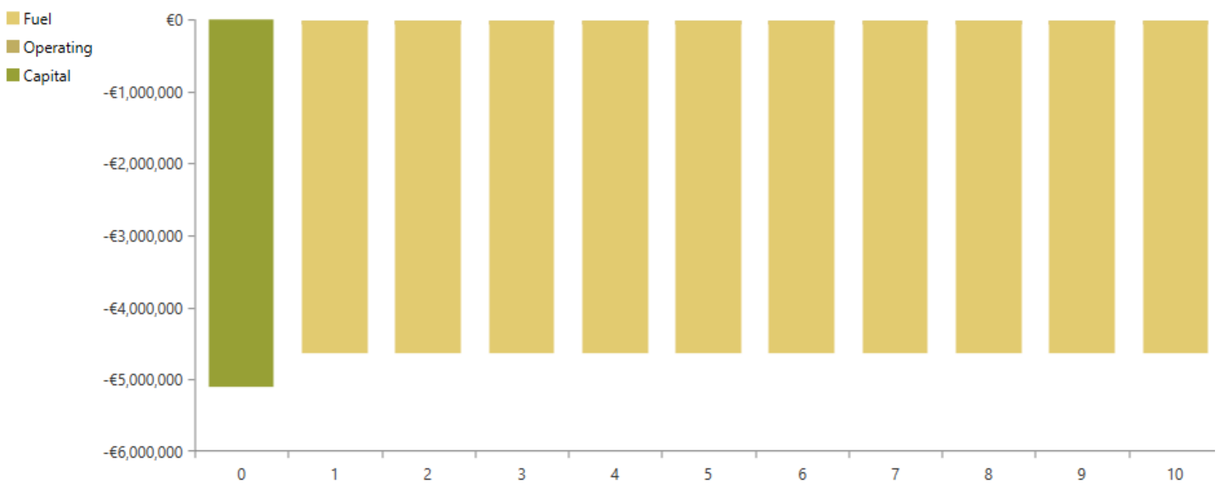


Figure 29 . Cash flow for Scenario 1.

4.3 Scenario 2

In scenario 2, the configuration will remain the same as scenario 1 while installing a battery storage bank to combat the excess electricity noticed. The search space for the photovoltaic arrays will be set at 1000-1200-1800-2500-3000-3200 kW. In this scenario the strorage system will be consisted of Hoppecke 24 OPzS 3000. The number of days of autonomy will be set at 1 day. Even though choosing [24] 3-5 days generally make an autonomous system stable, 1 day is chosen because of the low excess electricity noticed in scenario 2. This will set the battery search space strings at 188 . The diesel generators will remain as is in the base scenario to provide load that can not be met with solar generation.

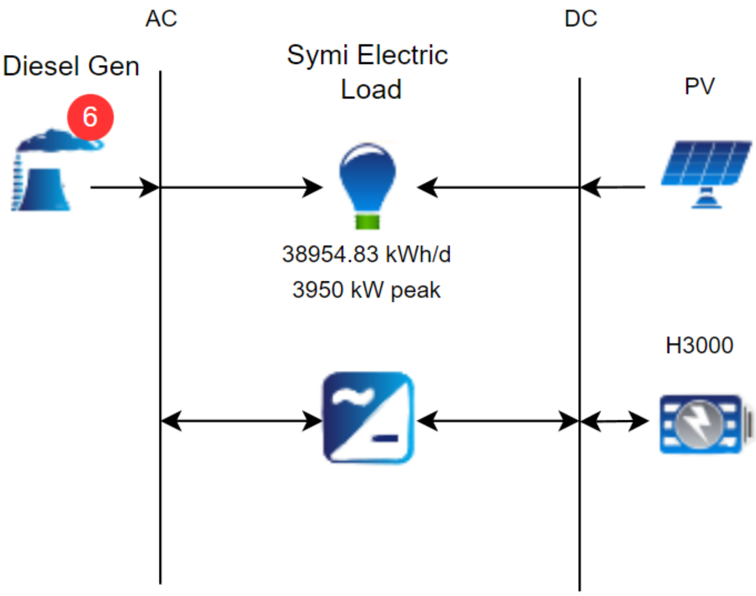


Figure 29. Scenario 2 used for simulation in HOMER

The architecture result HOMER output are the shown in table #. It is noted that in this case there in no excess electricity production due. This is the result of non existing battery bank. The results of the excess electricity production compared to the load are show in figure #.

System	PV(kW)	S16R-PTA G1	S16R-PTA G2(kW)	MTU 12V 4000G 60 (kW)	MTU 12V 4000G 60 (kW)	S16R-PTA G3(kW)	S16R-PTA G4(kW)	H3000	Converter (kW)	Excess Elec.(%)
Scenario 3	3,200	900	900	700	700	900	900	2,256	1,975	0

Table 21 . HOMER PRO Optimised Architecture for scenario 2

More specifically each component is presented in the table below:

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
MITSUBISHI S16R-PTA G1	5,256,989	35.6	707	1,215,171	7,431
MITSUBISHI S16R-PTA G2	2,734,606	18.8	457	634,425	5,983
MITSUBISHI S16R-PTA G3	949,029	6.51	368	220,719	2,576
MITSUBISHI S16R-PTA G3	270,239	1.85	305	63,047	914
MTU 12V 4000G60	177,275	1.22	176	53,153	1,010
MTU 12V 4000G60	-	-	-	-	1.00
Installed PVs	5,185,006	35.6	592	-	4,386

Table 22. HOMER PRO component details for scenario 2

The load requirement on the island is met by 5 of the present power systems' 6 diesel generators, with the 6th only operating for one hour. In this scenario, the 5 diesel generators currently placed on the island provide the majority of the production needed to meet the needs of the load. Conventional diesel generators account for almost 64.4% of total output. The low diesel generator operational hours of MTU 12V 4000G60, imply that the system might handle less conventional units, keeping in mind that this simulation has a very strict parameter of 1% annual shortage. In this scenario, Renewable energy sources, account for 35.6% of total energy production for the island’s load requirement. Figure # shows the monthly electrical generation of each component.

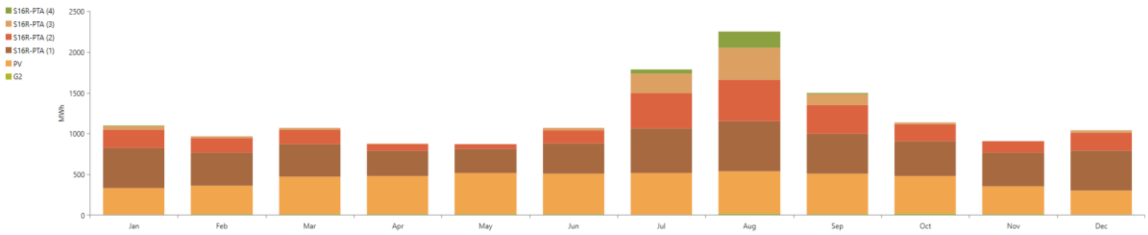


Figure 30 . Monthly Electrical Production of Scenario 3.

In this case, it is to be expected that Photovoltaics will remain the same as scenario 2. Figure # and Table # depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 3200 kW with a maximum power output of 2,805 kW.The total hours of operation of PV panels remains the same, which is to be expected at 4386 h/year which is about 12 hours per day.

Quantity	Value	Units
Rated Capacity	3,200	kW
Mean Output	592	kW
Mean Output	14,205	kWh/d
Capacity Factor	18.5	%
Total Production	5,185,006	kWh/yr
Minimum Output	0	kW
Maximum Output	2,807	kW
PV Penetration	36.5	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0678	€/kWh

Table 23. Solar PV simulation Results of scenario 2

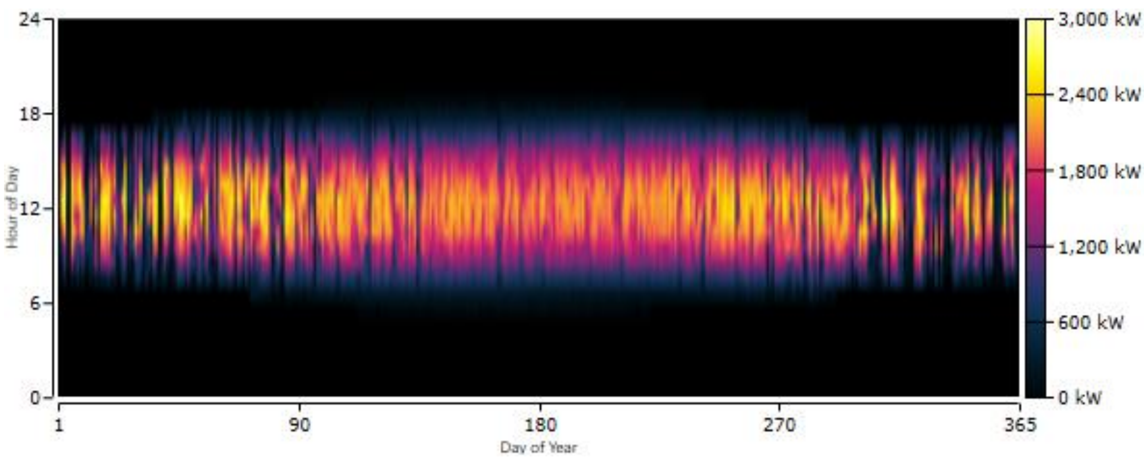


Figure 31 . Hourly PV Power Production of Scenario 2

In this scenario an storage system is installed which is consisted from Hoppecke 24 OPzS 3000 lead acid batteries, the hybrid system's energy storage is a substantial new parameter. The Renewable energy sources only charged the batteries based on the Load. Observing the approach for dispatching from Figure # below, it can be deduced that the battery is mostly at a low level of charge during the year since the low renewable energy source excess electricity. Due to the low load compared to summer months, the battery shows higher state of charge mostly during the spring months. The results of simulations of battery schemes are shown in Table 19. the results of which are presented in the table below:

Quantity	Value	Units
Batteries	2,256	qty.
String Size	12.0	batteries
Strings in Parallel	188	strings
Bus Voltage	24.0	V
Autonomy	6.96	hr
Storage Wear Cost	0.156	€/kWh
Nominal Capacity	16,129	kWh
Usable Nominal Capacity	11,290	kWh
Lifetime Throughput	7,456,949	kWh
Expected Life	10.0	yr
Average Energy Cost	0	€/kWh
Energy In	791,929	kWh/yr
Energy Out	691,529	kWh/yr
Storage Depletion	11,290	kWh/yr
Losses	111,690	kWh/yr
Annual Throughput	745,695	kWh/yr

Table 24. Storage simulation Results of scenario 2

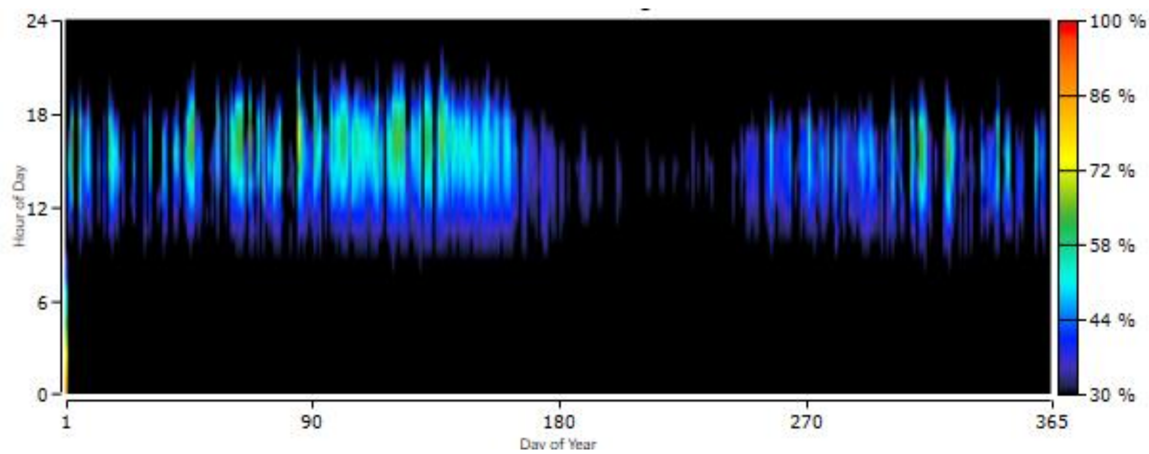


Figure 32 . Hourly Battery State-of-Charge Scenario 2

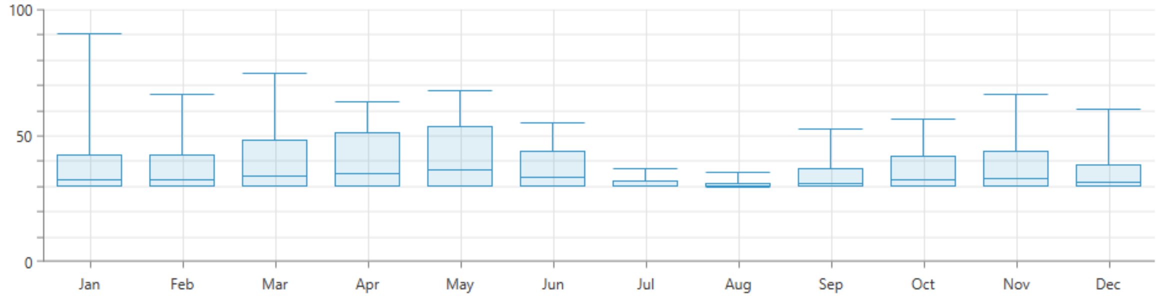


Figure 33 . Monthly Battery State-of-Charge Scenario 2

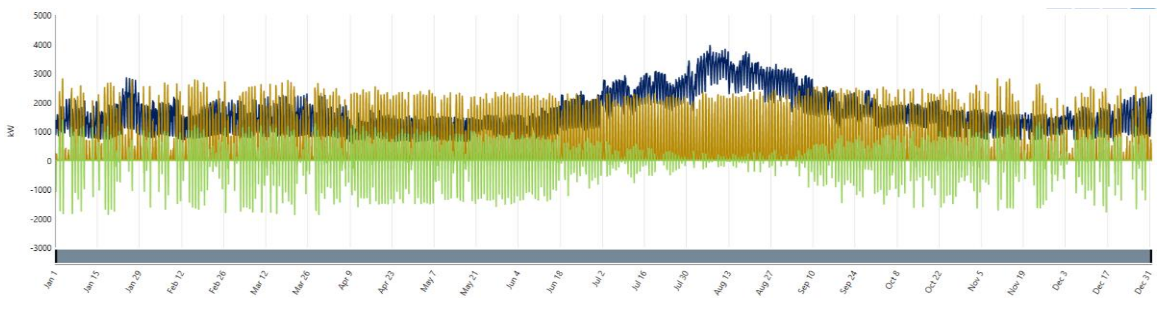


Figure 34 . Hourly PV Power Production, storage state of charge and load demand of the system in Scenario 2

From figure 34 it is observed that besides peak load months the system producses excess electricity during the day. That's the charging window for the battery storage to charge. Unfortunately the slow charging times and the low excess electricity keep the state of charge

of the battery bank relatively low. This configuration results in 0 excess electricity unlike scenario 2.
Economic Characteristic of Scenario 3:

Comparing the costs of scenario 1 and 2 the fuel costs for scenario 1 come up at € 4,660,999.776/year while at scenario 2 for 4,157,951.76€. That is € 503,048.016/year savings in fuel compared to scenario 1. It shall also be noticed that the renewable penetration rose from 25.9% to 33.9%

Total fuel consumed	**2,186,514**	**L**
Avg fuel per day	5,990	L/day
Avg fuel per hour	250	L/hour

Table 25. Yearly fuel consumption Results of scenario 2

About the system costs, it is to be expected to have a much larger initial capital requied than scenario 1 since besides the installment of PV arrays, the cost of batteries end up at €3,293,760.00 alone.

Scenario	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(L/yr)
Scenario 2	79,474,310	0.3709	4,718,792	€8,366,360	34%	2,179,220

Table 26. System results for scenario 2

Component	Capital(€)	Replacement(€)	O&M(€)	Fuel(€)	Total(€)
MITSUBISHI S16R-PTA	€0.00	€0.00	€0.00	€34,938,395.92	€34,938,395.92
MITSUBISHI S16R-PTA (1)	€0.00	€0.00	€0.00	€18,240,877.74	€18,240,877.74
MITSUBISHI S16R-PTA (2)	€0.00	€0.00	€0.00	€6,346,067.17	€6,346,067.17
MITSUBISHI S16R-PTA (3)	€0.00	€0.00	€0.00	€1,812,725.70	€1,812,725.70
Hoppecke 24 OPzS 3000	€3,293,760.00	€0.00	€509,938.38	€0.00	€3,803,698.38
Installed PVs	€4,480,000.00	€0.00	€819,759.09	€0.00	€5,299,759.09
MTU 12V 4000G60	€0.00	€0.00	€0.00	€1,528,249.71	€1,528,249.71
Other	€0.00	€0.00	€6,911,935.24	€0.00	€6,911,935.24
System Converter	€592,600.00	€0.00	€0.00	€0.00	€592,600.00
System	€8,366,360.00	€0.00	€8,241,632.71	€62,866,316.23	€79,474,308.94

Table 26. Analysis of system costs for scenario 2

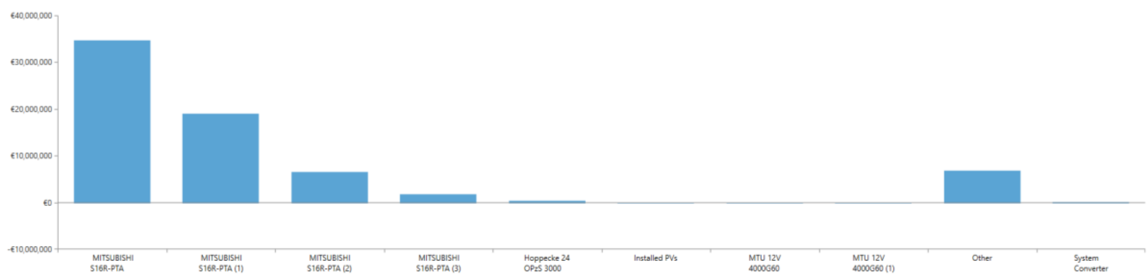


Figure 35 . Net Present Cost Summary by component for Scenario 2

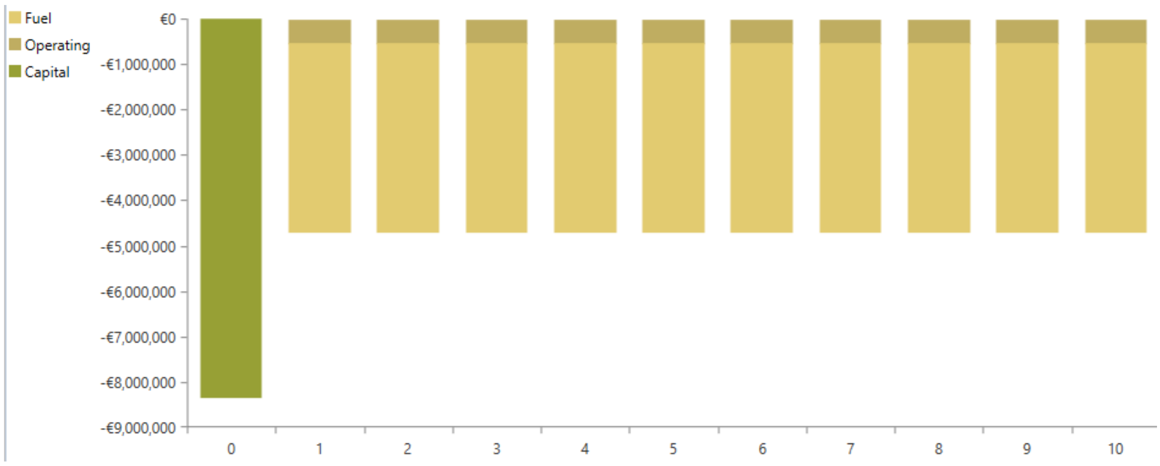


Figure 36 . Cash flow for Scenario 2

4.4 Scenario 3

In scenario 3, the configuration will remain the same as scenario 2 while replacing the battery storage bank with Lithium-Ion technology . The search space for the photovoltaic arrays will be set at 1000-1200-1800-2500-3000-3200 kW. In this scenario the strorage system will be consisted of PowerPlus Energy LiFe4833. To get the same autonomy as scenario 2, the string size of LiFe4833 batteries will be set at 3,444 with a string size of 1 . The advantage of Li-Ion batteries is the faster charge and discharge time compared to the Lead-Acid batteries, lower volume due to bigger energy density storage and near zero operational costs.[30]. The diesel generators will remain as is in the base scenario to provide load that can not be met with solar generation.

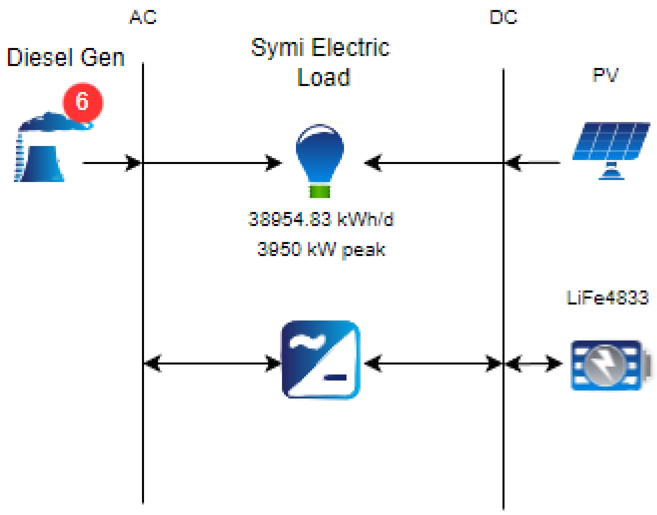


Figure 37 . Scenario 4 used for simulation in HOMER

The architecture result HOMER output are the shown in table #. It is noted that in this case there in no excess electricity production. This is the result of non existing battery bank. The results of the excess electricity production compared to the load are show in figure #.

System	PV(kW)	S16R-PTA G1	S16R-PTA G2(kW)	MTU 12V 4000G 60 (kW)	MTU 12V 4000G 60 (kW)	S16R-PTA G3(kW)	S16R-PTA G4(kW)	LiFe4833	Converter (kW)	Excess Elec.(%)
Scenario 3	3,200	900	900	700	-	900	900	3,444	988	0

Table 27 . HOMER PRO Optimised Architecture for scenario 3

More specifically each component is presented in the table below:

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
MITSUBISHI S16R-PTA G1	5,962,614	41.0	689	1,378,520	8,650
MITSUBISHI S16R-PTA G2	2,563,692	17.6	435	595,076	5,887
MITSUBISHI S16R-PTA G3	674,564	4.64	342	157,043	1,997
MITSUBISHI S16R-PTA G4	109,465	0.753	261	25,993	420
MTU 12V 4000G60	41,125	0.283	175	12,338	235
MTU 12V 4000G60	-	-	-	-	-
Installed PVs	5,185,006	35.7	592	-	4,386
System	14,536,466	100			

Table 28. HOMER PRO component details for scenario 3

Like scenario 2,the load requirement on the island is met by 5 of the present power systems' 6 diesel generators, with the 6th only operating for one hour. In this scenario, the 5 diesel generators currently placed on the island provide the majority of the production needed to meet the needs of the load with one diesel genarator working for one hour during peak load. Conventional diesel generators account for almost 64.6% of total output. In this scenario, Renewable energy sources, account for 35.4% of total energy production for the island's load requirement. Figure # shows the monthly electrical generation of each component.

In this case, it is to be expected that Photovoltaics will remain the same as scenario 3. Figure # and Table # depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 3200 kW with a maximum power output of 2,805 kW.The total hours of operation of PV panels remains the same, which is to be expected at 4386 h/year which is about 12 hours per day.

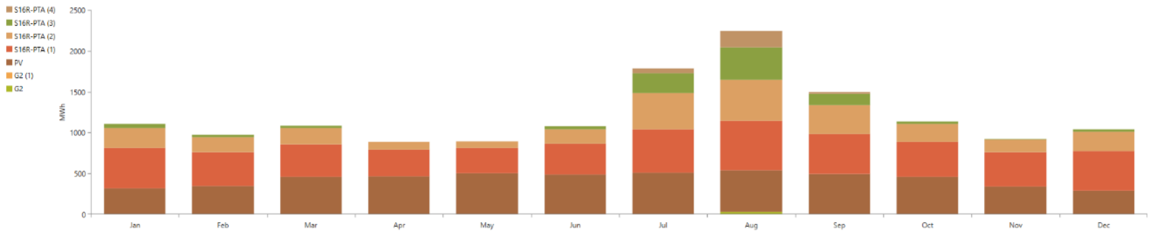


Figure 38 . Monthly Electrical Production of Scenario 4.

Quantity	Value	Units
Rated Capacity	3,200	kW
Mean Output	592	kW
Mean Output	14,205	kWh/d
Capacity Factor	18.5	%
Total Production	5,185,006	kWh/yr
Minimum Output	0	kW
Maximum Output	2,807	kW
PV Penetration	36.5	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0678	€/kWh

Table 29. Solar PV simulation Results of scenario 3

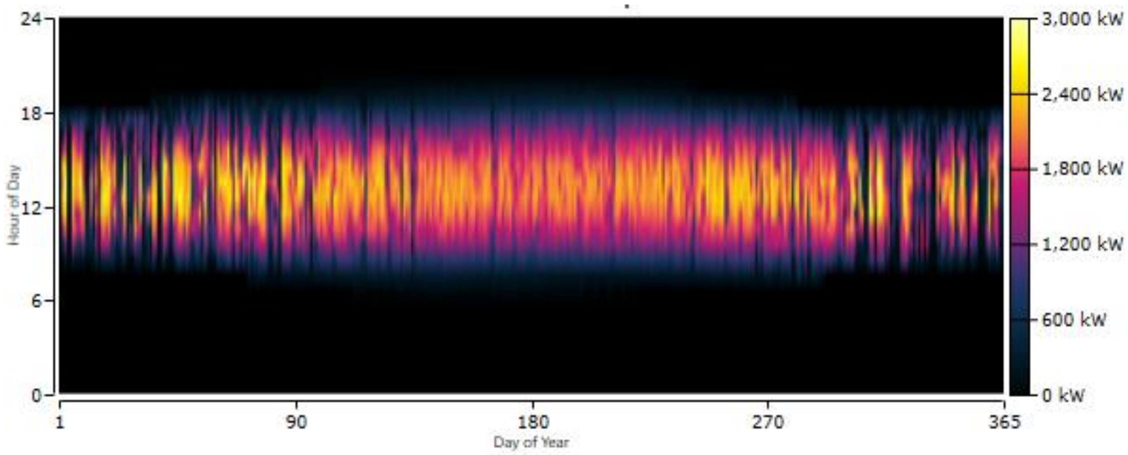


Figure 39 . Hourly PV Power Production of Scenario 4.

In this scenario an storage system is installed which is consisted only from PowerPlus Energy LiFe4833 Lithium-Ion batteries.The Renewable energy sources only charged the batteries based on the Load, storing most excess electricity. Observing the approach for dispatching from Figure # below, the fast charging times of Lithium-Ion batteries contribute to higher average state of charge compared to Lead-Acid batteries[31], unfortunatelly the low volume of batteries result The results of simulations of battery schemes are shown in Table 19. the results of which are presented in the table below:

Quantity	Value	Units
Batteries	3,444	qty.
String Size	1	batteries
Strings in Parallel	3,444	strings
Bus Voltage	51.2	V
Autonomy	6.95	hrs.
Storage Wear Cost	0.147	€/kWh
Nominal Capacity	11,285	kWh
Usable Nominal Capacity	11,285	kWh
Lifetime Throughput	17,956,987	kWh
Expected Life	10.0	yrs.
Average Energy Cost	0	€/kWh
Energy In	1,821,209	kWh/yr
Energy Out	1,759,418	kWh/yr
Storage Depletion	11,285	kWh/yr
Losses	73,076	kWh/yr

Annual Throughput	1,795,699	kWh/yr

Table 30. Storage simulation Results of scenario 3

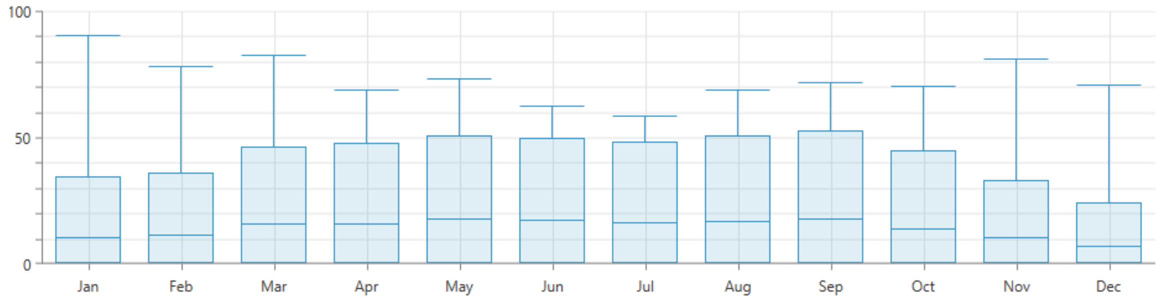


Figure 40 . Monthly Battery State-of-Charge Scenario 3.

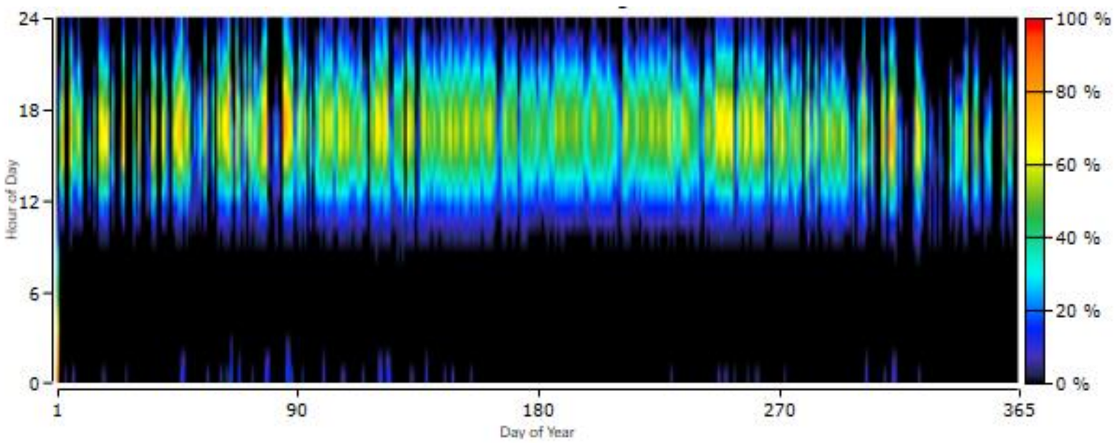


Figure 41 . Hourly Battery State-of-Charge Scenario 3.

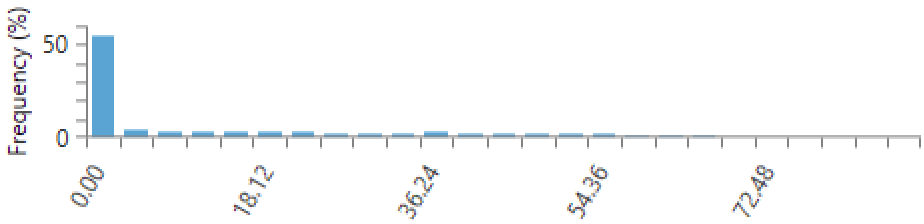


Figure 42 . Battery State-of-Charge frequency Scenario 3.

Even though the battery system simulated in scenario 2 is smaller than scenario 3 the low charging time of this system makes up for it. It can be noticed that the batteries have significantly higher state of charge cosnidering that Lead-Acid batteries have a minimum Depth-of-charge of 30% while Lion batteries have 0%. Even though the autonomy of the system is lower compared to scenario 2, the fast charge time has its own advantages since this configuration results in 0 excess electricity unlike scenario 2.

Economic Characteristic of Scenario 3:

About the system costs, it is to be expected to have a much larger initial capital requied than scenario 2 since besides the installment of PV arrays, the bigger cost of batteries end up at €8,124,396.00. The economic aspects for the base system are presented in Table 31.Comparing the costs of scenario 2 and 3 the fuel costs for scenario 2 come up at € 4,660,999.776/year while at scenario 3 for 4,157,951.76€. That is € 503,048.016/year savings in fuel compared to scenario 2. It shall also be noticed that the renewable penetration rose from 25.9% to 34.2%

Total fuel consumed	2,168,569	L
Avg fuel per day	5,941	L/day
Avg fuel per hour	248	L/hour

Table 31. Yearly fuel consumption Results of scenario 3

Scenario	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(L/yr)
Scenario 3	€82,926,020	€0.3870	4,646,948	€12,900,696	34.2%	2,168,569

Table 32. System results for scenario 3

Normally Lion batteries have longer lifespans than Lead-Acid batteries and they tend to outpeform them in the long run.[24]

Component	Capital(€)	Replacement (€)	O&M(€)	Fuel(€)	Total(€)
MITSUBISHI S16R-PTA	€0.00	€0.00	€0.00	€39,634,991.65	€39,634,991.65
MITSUBISHI S16R-PTA (1)	€0.00	€0.00	€0.00	€17,109,536.57	€17,109,536.57
MITSUBISHI S16R-PTA (2)	€0.00	€0.00	€0.00	€4,515,262.84	€4,515,262.84
MITSUBISHI S16R-PTA (3)	€0.00	€0.00	€0.00	€735,837.81	€735,837.81
Installed PVs	€4,480,000.00	€0.00	€819,759.09	€0.00	€5,299,759.09
MTU 12V 4000G60 (1)	€0.00	€0.00	€0.00	€354,725.88	€354,725.88
Other	€0.00	€0.00	€6,855,207.05	€0.00	€6,855,207.05
PowerPlus Energy LiFe4833	€8,124,396.00	€0.00	€0.00	€0.00	€8,124,396.00
System Converter	€296,300.00	€0.00	€0.00	€0.00	€296,300.00
System	€12,900,696.00	€0.00	€7,674,966.14	€62,350,354.76	€82,926,016.90

Table 33. Analysis of system costs for scenario 3

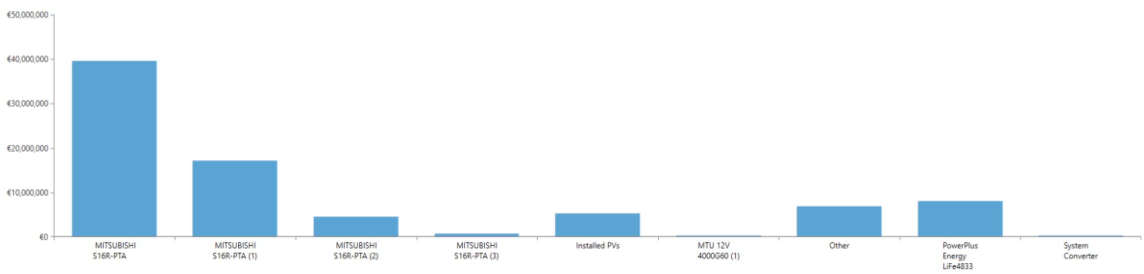


Figure 43. Net Present Cost Summary by component for Scenario 3

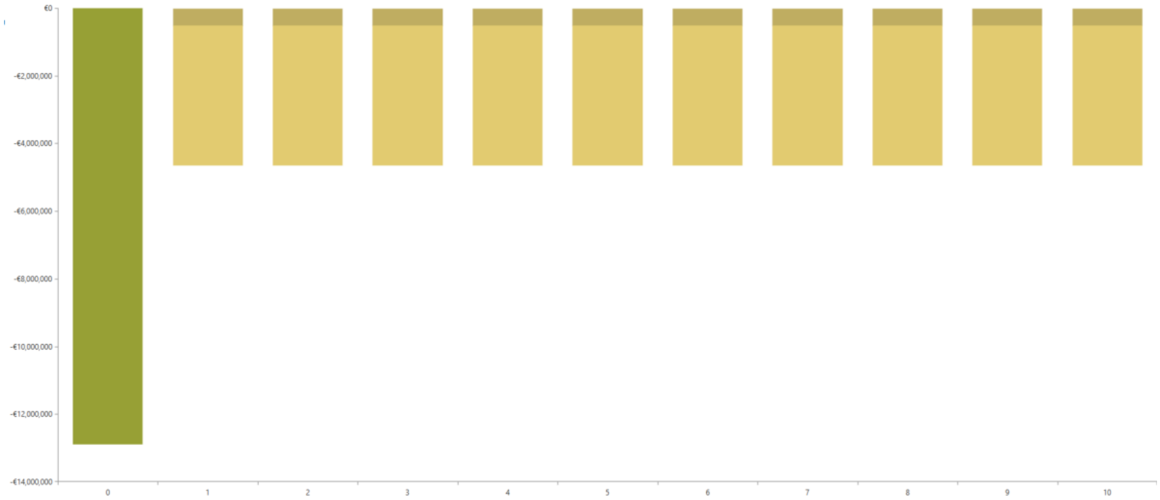


Figure 44 . Cash flow for Scenario 3

4.5 Scenario 4

In scenario 4, the optimal configuration with storage will be selected and wind turbines will be added. In this case scenario 2 with the Hoppecke 24 OPzS 3000 will be selected due to lower cost observed at the previous scenarios. The battery bank will be expanded to n_{day}=4 because there is more excess Renewable energy available to charge it.

Scenario 4 will consider the optimal solution of the Vestas V82 installation. The installation of this wind turbine has many challenges due to the small port of Symi and the road network of the island.

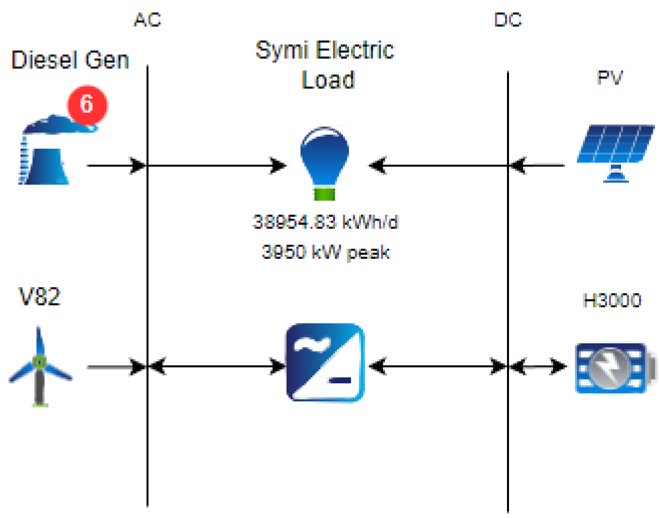


Figure 45 . Scenario 4 used for simulation in HOMER

The architecture result HOMER output are the shown in table 34. It is noted that in this case excess electricity exists in the system with a percentage of 5,04%. This excess electricity can be reduced to zero but expanding the battery bank more would increase the system costs making the investment not logical. The results of the average excess electricity production are shown in figure 52.

System	PV(kW)	V82	S16R-	S16R-PTA	S16R-PTA	S16R-PTA	MTU 12V	H3000	Converter (kW)	Excess Elec.(%)

			PTA G1	G2(kW)	G3(kW)	G4(kW)	4000G60 (kW)			
Scenario 5	3,200	2	900	900	900	900	700	9,024	2,222	5.08

Table 34 . HOMER PRO Optimised Architecture for scenario 4

More specifically each component is presented in the table below :

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
MITSUBISHI S16R-PTA G1	1,489,014	9.39	624	344,499	2,387
MITSUBISHI S16R-PTA G2	903,263	5.69	504	209,359	1,793
MITSUBISHI S16R-PTA G3	406,736	2.56	383	94,551	1,063
MITSUBISHI S16R-PTA G4	124,710	0.786	303	29,084	412
MTU 12V 4000G60	88,892	0.560	176	26,639	505
Vestas V82 [1.6 MW]	7,665,893	48.3	875	-	7,313
Installed PVs	5,185,006	32.7	592	-	4,386
System	15,185,743	100			

Table 36. HOMER PRO component details for scenario 4

Unlike any other scenario tested till now, the load requirement the is met by mainly by renewable energy sources, achieving a renewable fraction of 78.8%. In this scenario, the 5 diesel generators currently placed on the island only supplement energy required mainly during peak months. Conventional diesel generators account for only 18.99% of total output. Figure # shows the monthly electrical generation of each component.

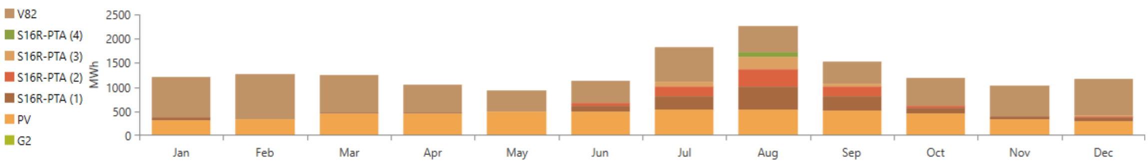


Figure 46 . Monthly Electrical Production of Scenario 4

In this case, it is to be expected that Photovoltaics will remain the same as scenario 3, since in that scenario there was zero excess electricity. Figure 47 and Table 37 depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 3200 kW with a maximum power output of 2,805 kW.The total hours of operation of PV panels remains the same, which is to be expected at 4386 h/year.

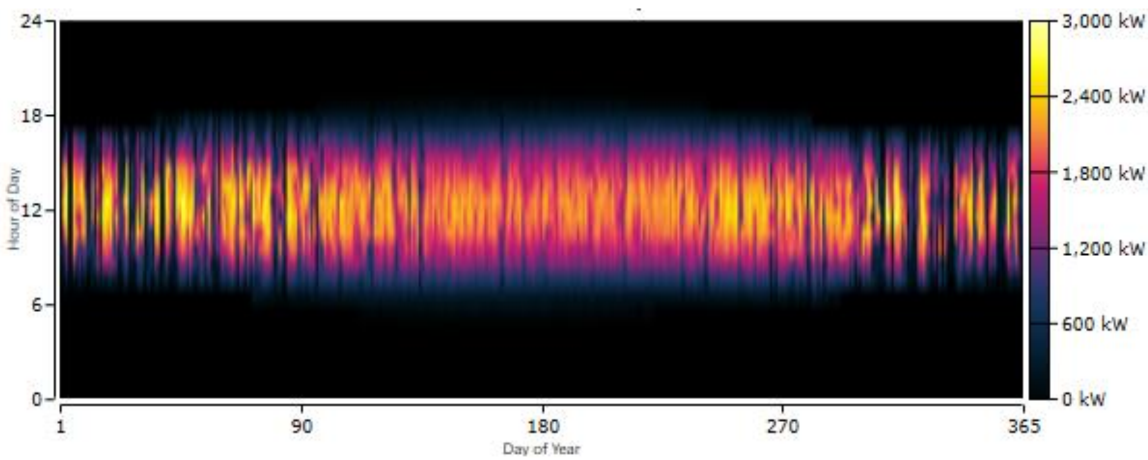


Figure 47 . Hourly PV Power Production of Scenario 4

Quantity	Value	Units
Rated Capacity	3,200	kW
Mean Output	592	kW
Mean Output	14,205	kWh/d
Capacity Factor	18.5	%
Total Production	5,185,006	kWh/yr
Minimum Output	0	kW
Maximum Output	2,807	kW
PV Penetration	36.5	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0678	€/kWh

Table 37. Solar PV simulation Results of scenario 4

This is the first scenario in which wind turbines are tested. Figure 48 depict the hourly output power of Vestas V82. Table 38 depicts the electricity simulation results. Unlike solar production electricity generation is maximized during the winter season, with February,March and January having the largest average production respectively . The total rated capacity of the Vestas V82 on this scenario is 3,300 kW with a maximum power output of 3,241 kW.The total hours of operation of the wind turbines amount to 7,194 hrs/yr or 19 hours per day.

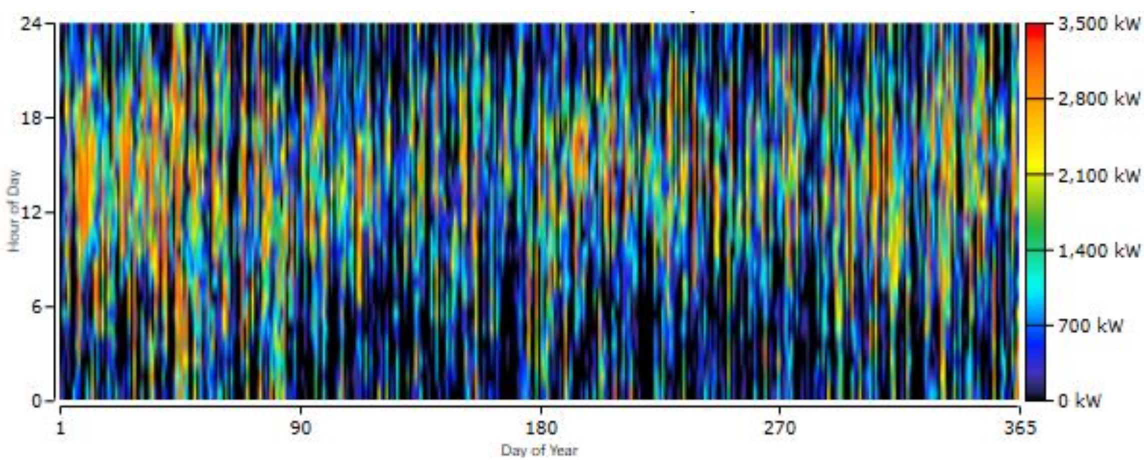


Figure 48 . Hourly Wind Turbine Power output of Scenario 4

Quantity	Value	Units
Total Rated Capacity	3,300	kW
Mean Output	875	kW
Capacity Factor	26.5	%
Total Production	7,665,893	kWh/yr
Minimum Output	0	kW
Maximum Output	3,300	kW
Wind Penetration	53.9	%
Hours of Operation	7,313	hrs/yr
Levelized Cost	0.105	€/kWh

Table 38. Wind Turbines simulation Results of scenario 4

In this scenario an expanded storage system of scenario 2 is installed which is consisted Hoppecke 24 OPzS 3000 lead acid batteries. The Renewable energy sources charged the batteries based on the excess energy produced. Observing the state of charge frequency from Figure # below,it is noticed that the batteries remain at a depth of charge of 30% with a frequency of 26.69%. Due to the low load compared to summer months, the battery shows higher state of charge mostly during the spring months. The results of simulations of battery schemes are shown in Table 19. the results of which are presented in the table below:

Quantity	Value	Units
Batteries	9,024	qty.
String Size	12.0	batteries
Strings in Parallel	752	strings
Bus Voltage	24.0	V
Autonomy	27.8	hr
Storage Wear Cost	0.156	€/kWh
Nominal Capacity	64,515	kWh
Usable Nominal Capacity	45,161	kWh
Lifetime Throughput	34,574,222	kWh
Expected Life	10.0	yr
Average Energy Cost	0	€/kWh

Energy In	3,693,687	kWh/yr
Energy Out	3,206,281	kWh/yr
Storage Depletion	32,038	kWh/yr
Losses	519,443	kWh/yr
Annual Throughput	3,457,422	kWh/yr

Table 39. Storage simulation Results of scenario 4

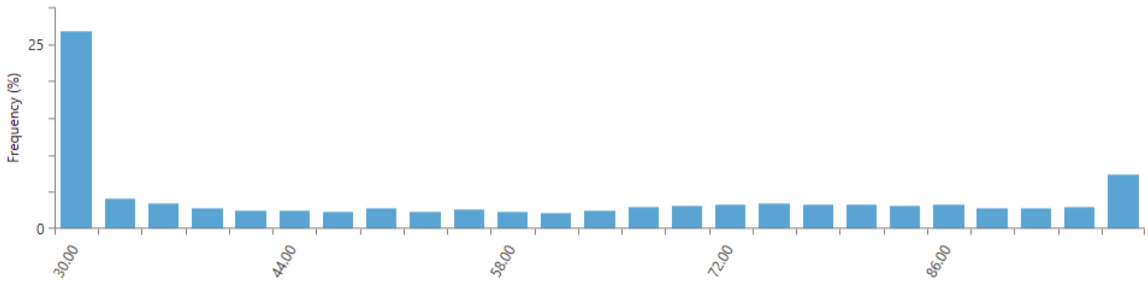


Figure 49 . Hoppecke 24 OPzS 3000 state of charge frequency of Scenario 4

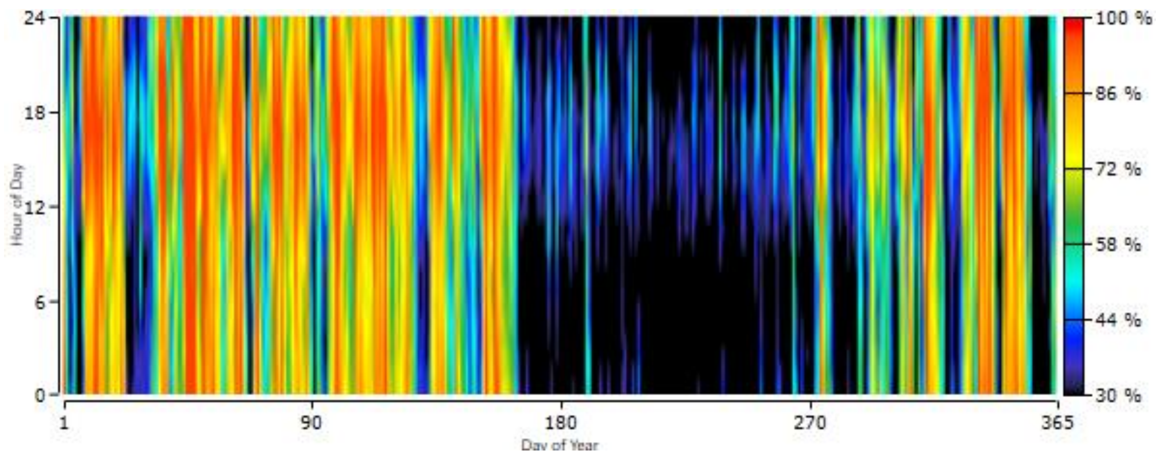


Figure 50. Hoppecke 24 OPzS 3000 state of charge of Scenario 4

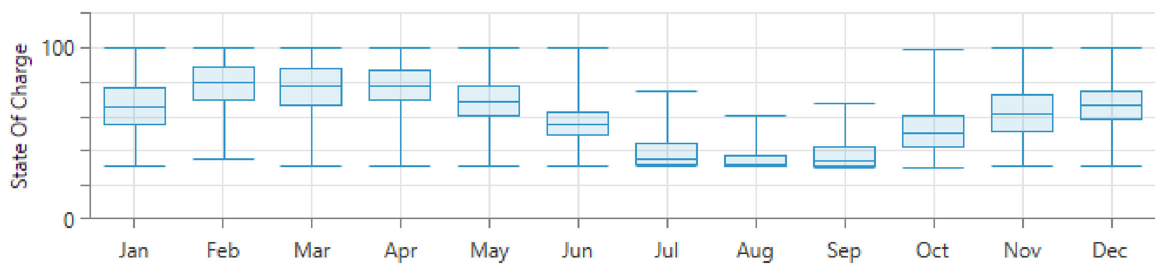


Figure 51 . Hoppecke 24 OPzS 3000 monthly average state of charge of Scenario 4

Excess electricity is observed during peak production months of wind power output and low load demand. All months except the three summer ones, are observed to have excess electricity with February having the maximum wasted energy of a daily average of 345.5 kW.The least average excess electricity between those months is October with an average of 5 kW excess.

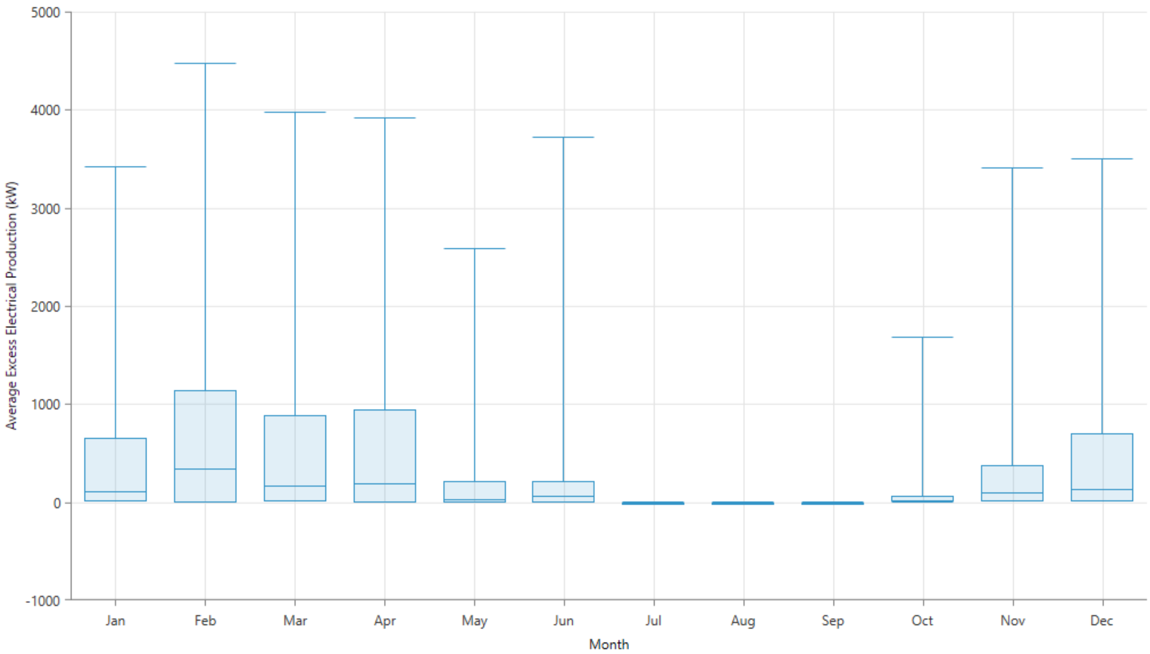


Figure 52 . Monthly average excess electrical production of Scenario 4.

Economic Characteristic of Scenario 4:

In scenario 4, it is to be expected that the initial capital required will be significantly larger than all the other scenarios. That is because the installment of wind tubrines is huge endeavor. Also the expanded storage bank required a big amount of capital. Comparing the fuel costs of scenario 2 and 4 the fuel costs for scenario 2 come up at 4,157,951.76€/year while for scenario 4 at 1,343,476.224€. That is € 2,814,475.536 €/year savings in fuel compared to scenario 2. It shall also be noticed that the renewable penetration rose from 33.9% to 78.8%

Total fuel consumed	704,128	L
Avg fuel per day	1,929	L/day
Avg fuel per hour	80.4	L/hour

Table 40. Yearly fuel consumption Results of scenario 3

The economic aspects for the system are presented in Table 41

Scenario	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(L/yr)
Scenario 4	€54,466,330	€0.2542	1,794,707	€27,421,715.00	78.8%	704,128

Table 41. System results for scenario 4

Component	Capital(€)	O&M(€)	Fuel(€)	Total(€)
MITSUBISHI S16R-PTA	€0.00	€0.00	€9,904,970	€9,904,970
MITSUBISHI S16R-PTA (1)	€0.00	€0.00	€6,019,358	€6,019,358
MITSUBISHI S16R-PTA (2)	€0.00	€0.00	€2,718,515	€2,718,515
MITSUBISHI S16R-PTA (3)	€0.00	€0.00	€836,227	€836,227.63
Hoppecke 24 OPzS 3000	€13,175,040	€679,917	€0.00	€13,854,957
Installed PVs	€4,480,000	€819,759	€0.00	€5,299,759
MTU 12V 4000G60	€0.00	€0.00	€765,907	€765,907
Other	€0.00	€2,225,865	€0.00	€2,225,865
System Converter	€666,675	€0.00	€0.00	€9,904,970
Vestas V82 [1665kW]	€9,100,000	€3,074,096	€0.00	€6,019,358
System	€27,421,715	€6,799,639	€20,244,979	€2,718,515

Table 42. Analysis of system costs for scenario 4

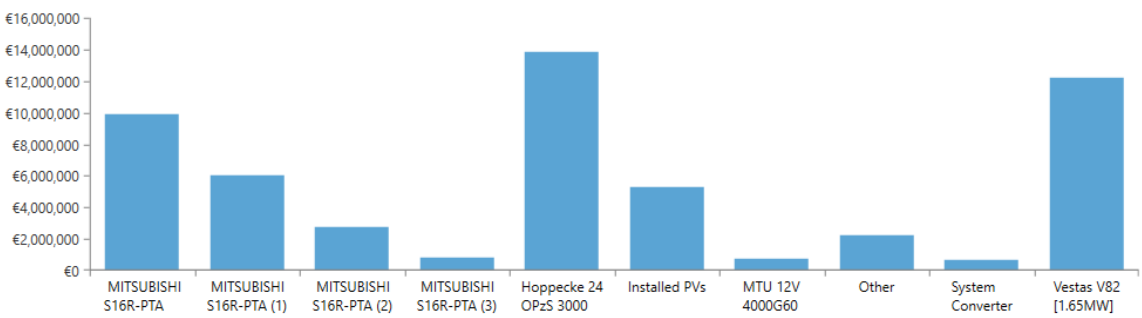


Figure 53 . Net Present Cost Summary by component for Scenario 4

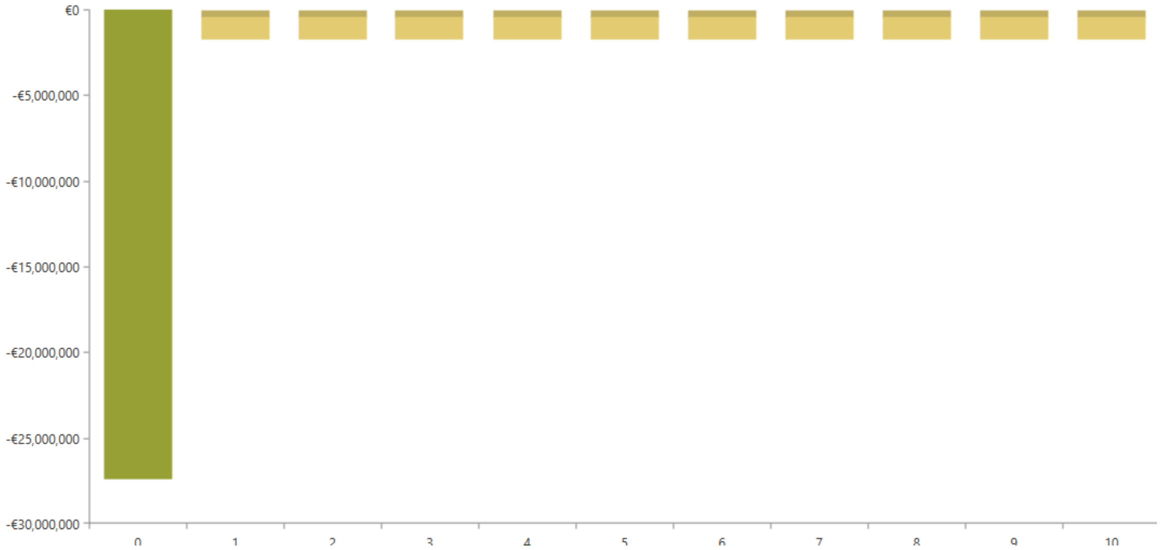


Figure 54. Cash flow for Scenario 4

4.6 Scenario 5

In scenario 5, the XANT L-33 wind turbines will replace the vestas V82. Otherwise the set up will remain the same as scenario 5. XANT L-33 wind turbines were chosen because of their easy transport and installation. The installation of this wind turbine is very easy since it ships in 40-feet containers and they are able to be assempled without many heavy machinery.

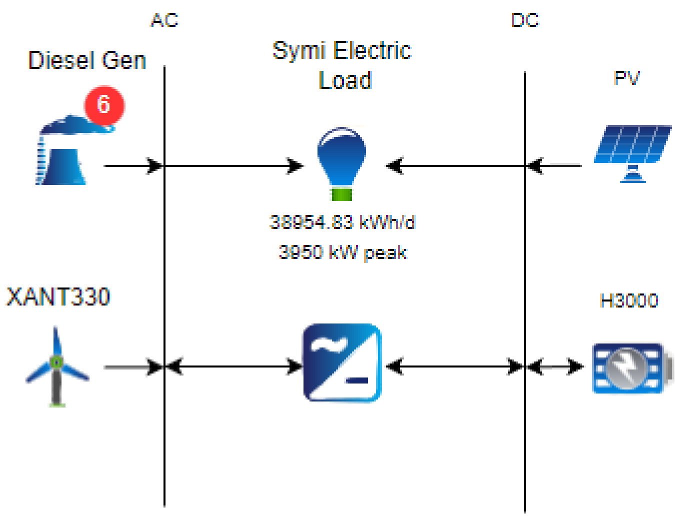


Figure 55. Scenario 5 used for simulation in HOMER

The architecture result HOMER output are the shown in table 43. It is noted that in this case excess electricity exists in the system with a percentage of 1.16%. This excess electricity can be reduced to zero but expanding the battery bank more would increase the system costs making the investment not logical. The results of the excess electricity production compared to the load are show in figure 63.

System	PV(kW)	XANT330	S16R-PTA G1	S16R-PTA G2(kW)	S16R-PTA G3(kW)	S16R-PTA G4(kW)	MTU 12V 4000G60 (kW)	H3000	Converter (kW)	Excess Elec.(%)
Scenario 5	3,200	10	900	900	900	900	700	9,024	2,222	4.34

Table 43 . HOMER PRO Optimised Architecture for scenario 5

More specifically each component is presented in the table below :

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
MITSUBISHI S16R-PTA G1	1,581,887	10.1	623	365,991	2,541
MITSUBISHI S16R-PTA G2	973,756	6.20	507	225,682	1,922
MITSUBISHI S16R-PTA G3	437,155	2.78	388	101,604	1,126
MITSUBISHI S16R-PTA G4	135,745	0.864	299	31,664	454
MTU 12V 4000G60	105,348	0.601	176	28,306	537
XANT L-33 [330kW]	7,312,160	46.5	728	-	7,194
Installed PVs	5,179,126	33	592	-	4,386
System	15,714,269	100			

Table 44. HOMER PRO component details for scenario 5

Since the installed wind turbines have the same power as scenario 5, the load requirement the is met by mainly by renewable energy sources, achieving a renewable fraction of 77.3%. In this scenario, the 5 diesel generators currently placed on the island mainly supplement energy required mainly during peak months. Conventional diesel generators account for only 20,545% of total output, more than scenario 4. Figure # shows the monthly electrical generation of each component.

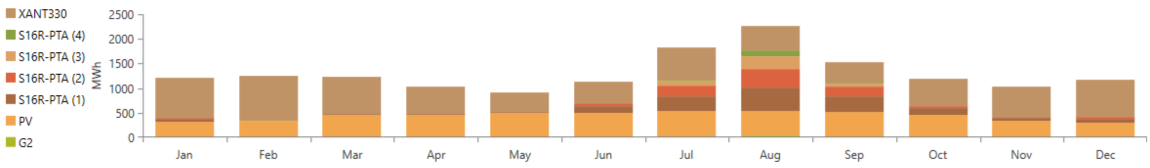


Figure 56. Monthly Electrical Production of Scenario 5

In this case, it is to be expected that Photovoltaics will remain about the same as scenario 4, since the set up is exactly the same . Figure 57 and Table 45 depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 3200 kW with a maximum power output of 2,805 kW.The total hours of operation of PV panels remains the same, which is to be expected at 4386 h/year.

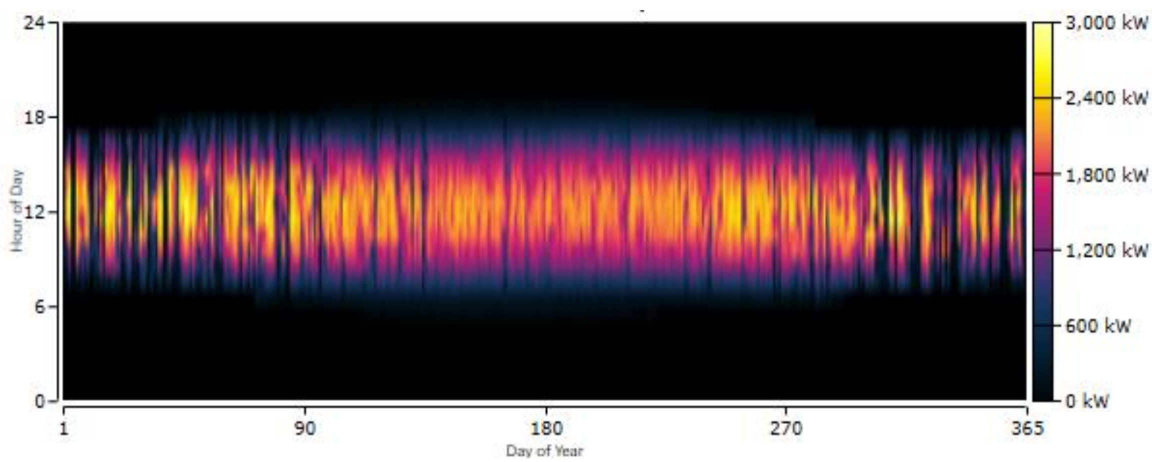


Figure 57. Hourly PV Power Production of Scenario 5

Quantity	Value	Units
Rated Capacity	3,200	kW
Mean Output	591	kW
Mean Output	14,189	kWh/d
Capacity Factor	18.5	%
Total Production	5,179,126	kWh/yr
Minimum Output	0	kW
Maximum Output	2,805	kW
PV Penetration	36.4	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0679	€/kWh

Table 45. Solar PV simulation Results of scenario 5

Figure 58 depict the hourly output power of XANT L-33. Table # depicts the wind electricity production simulation results. Unlike solar production electricity generation is maximized during the winter season, with February having the largest average production .From the summer months, July has the largest energy production. The total rated capacity of the XANT L-33 in this scenario is 3,300 kW with a maximum power output of 3,390 kW.The total hours of operation of the wind turbines amount to 7,227 hrs/yr or 19 hours per day.

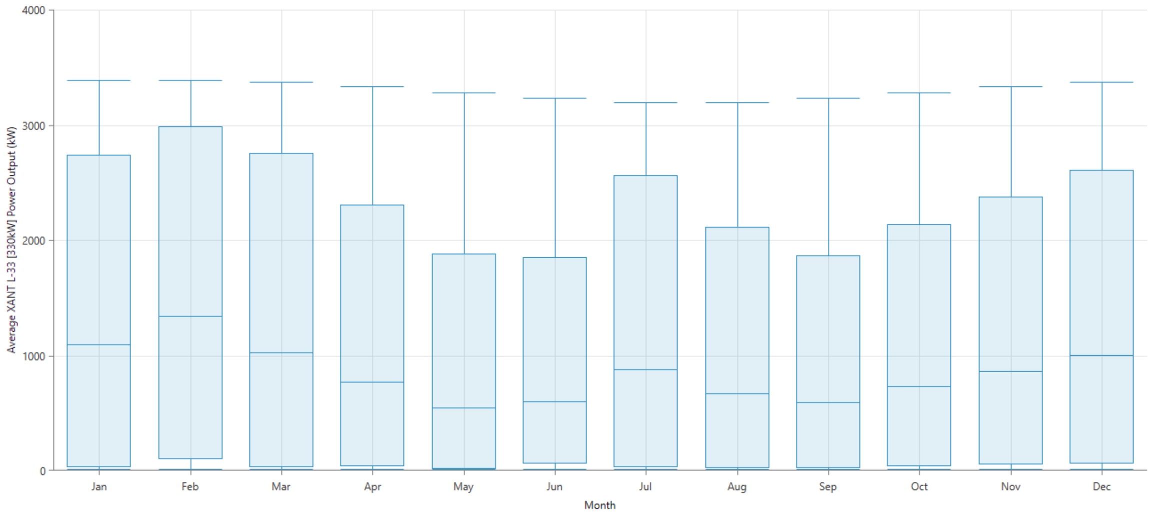


Figure 58. Monthly Power Output Average of XANT L-33 in scenario 6.

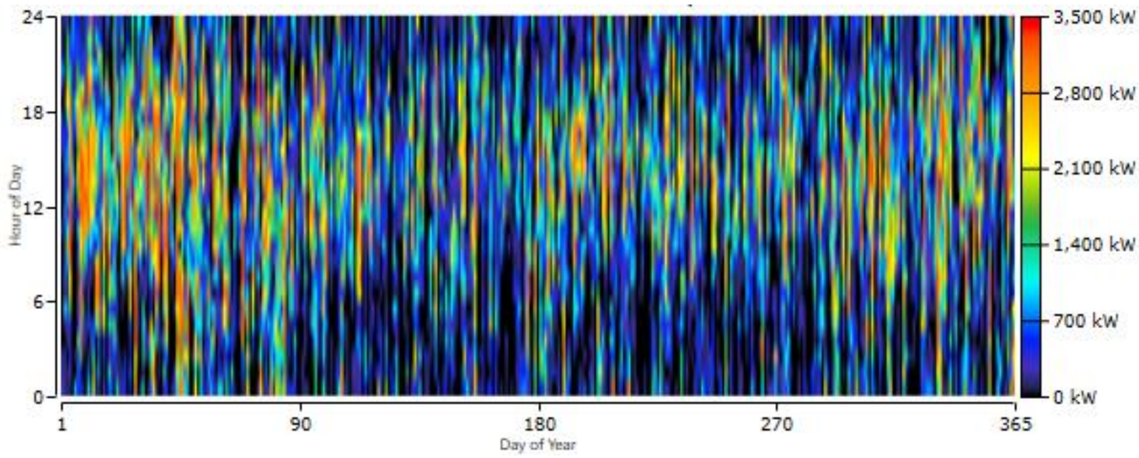


Figure 59. Hourly Wind Turbine Power output of Scenario 5

Quantity	Value	Units
Total Rated Capacity	3,300	kW
Mean Output	835	kW
Capacity Factor	25.3	%
Total Production	7,312,160	kWh/yr
Minimum Output	0	kW
Maximum Output	3,392	kW
Wind Penetration	51.4	%
Hours of Operation	7,227	hrs/yr

Levelized Cost	0.127	€/kWh

Table 46. Wind Turbines simulation Results of scenario 5

In this scenario the storage bank is the same as scenario 5 which is consisted Hoppecke 24 OPzS 3000 lead acid batteries. Observing the state of charge frequency from Figure # below,that the batteries remain at a depth-of-charge of 30% with a frequency of 28.68% and at depth-of-charge of 100% with a frequency of 6.40%. The big frequency of low depth-of-charge is due to the high load demand of summer months, where the batteries remain constantly at a low charge. The battery shows higher state of charge during the spring months. The results of simulations of battery schemes are shown in Table 19. the results of which are presented in the table below:

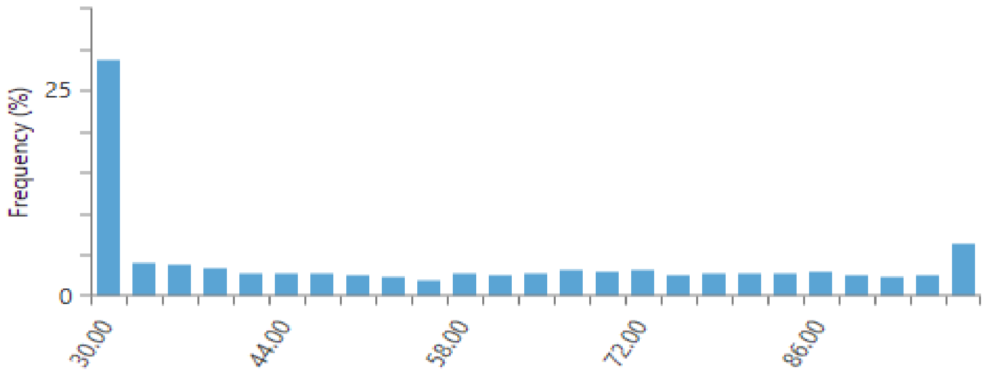


Figure 60. Hoppecke 24 OPzS 3000 state of charge frequency of Scenario 5

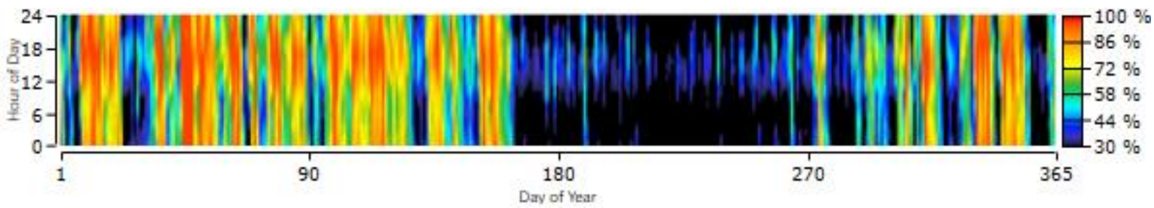


Figure 61. Hoppecke 24 OPzS 3000 state of charge of Scenario 5

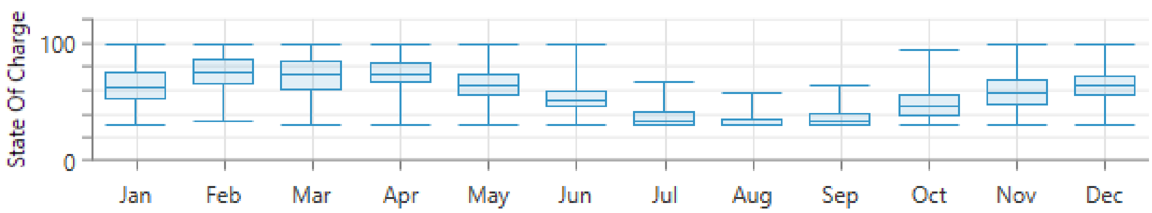


Figure 62. Hoppecke 24 OPzS 3000 monthly average state of charge of Scenario 5

Quantity	Value	Units
Batteries	8,640	qty.
String Size	12.0	batteries
Strings in Parallel	720	strings
Bus Voltage	24.0	V
Autonomy	26.6	hr
Storage Wear Cost	0.156	€/kWh
Nominal Capacity	61,770	kWh
Usable Nominal Capacity	43,239	kWh
Lifetime Throughput	33,299,760	kWh
Expected Life	10.0	yr
Average Energy Cost	0	€/kWh
Energy In	3,554,136	kWh/yr
Energy Out	3,088,093	kWh/yr
Storage Depletion	34,006	kWh/yr
Losses	500,049	kWh/yr
Annual Throughput	3,329,976	kWh/yr

Table 47. Storage simulation Results of scenario 5

Like scenario 4, excess electricity is observed during all months except July,August, September and October . Most excess electricity is observed during February with an average excess electricity of 326.04 kW. Least excess electricity is observed during May with an average of 17.98 kW.

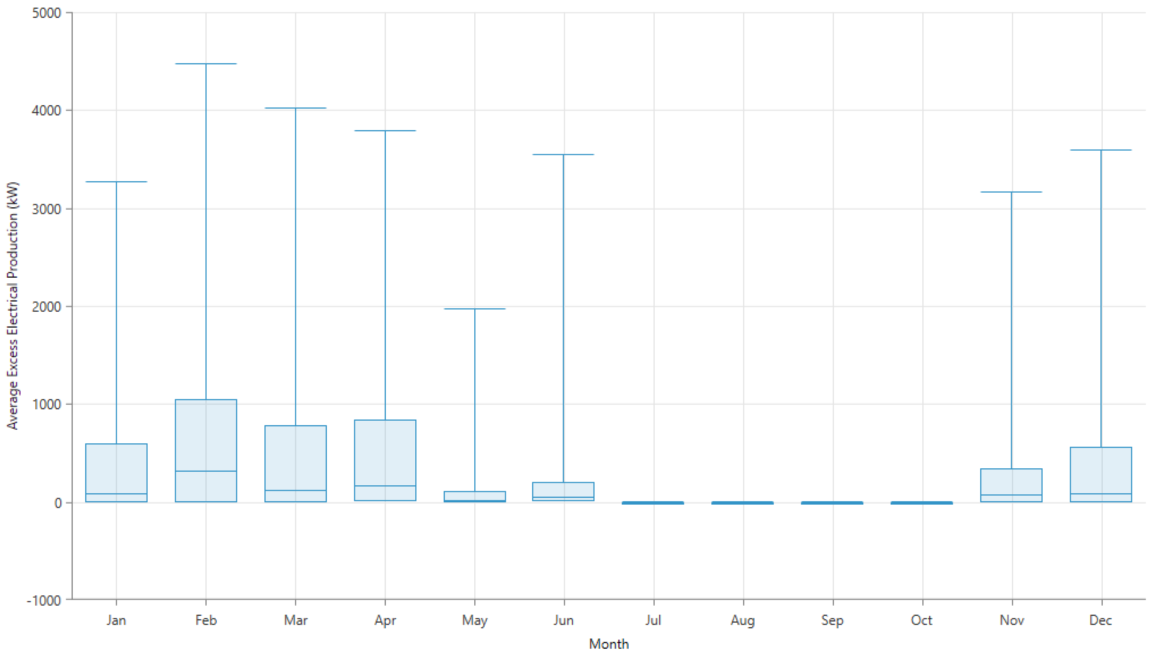


Figure 63 . Monthly average excess electrical production of Scenario 5.

Economic Characteristic of Scenario 5:

In scenario 5, it is to be expected that the capital required will be larger than scenario 4, that's because ten XANT L-33 will be required to have the same power output as two vestas V82.Comparing the costs of scenario 4 and 5 the fuel costs for scenario 5 come up at 1,437,197.184€/year while for scenario 4 at 1,343,476.224€/year. That is € 93,720.776€ /year more in fuel compared to scenario 4. It shall also be noticed that the renewable penetration fell from 78.8% to 77.3% .

Total fuel consumed	753,248	L
Avg fuel per day	2,064	L/day
Avg fuel per hour	86.0	L/hour

Table 48. Yearly fuel consumption Results of scenario 5

The economic aspects for the system are presented in Table 49

Scenario	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(L/yr)
Scenario 5	€57,237,510	€0.2671	1,942,812	€27,961,075	77.3%	753,248

Table 49. System results for scenario 5

Component	Capital(€)	O&M(€)	Fuel(€)	Total(€)
MITSUBISHI S16R-PTA	€0.00	€0.00	€10,522,92	€10,522,923
MITSUBISHI S16R-PTA (1)	€0.00	€0.00	€6,488,787	€6,488,787
MITSUBISHI S16R-PTA (2)	€0.00	€0.00	€2,921,311	€2,921,311
MITSUBISHI S16R-PTA (3)	€0.00	€0.00	€910,397.53	€910,397
Hoppecke 24 OPzS 3000	€12,614,400	€650,985	€0.00	€13,265,385
Installed PVs	€4,480,000	€819,759.09	€0.00	€5,299,759
MTU 12V 4000G60	€0.00	€0.00	€813,849.58	€813,849
Other	€0.00	€2,381,142	€0.00	€2,381,142
System Converter	€666,675	€0.00	€0.00	€10,522,923
XANT L-33 [330kW]	€10,200,000	€3,767,275	€0.00	€6,488,787
System	€27,961,075	€7,619,161	€21,657,269	€2,921,311

Table 50. Analysis of system costs for scenario 5

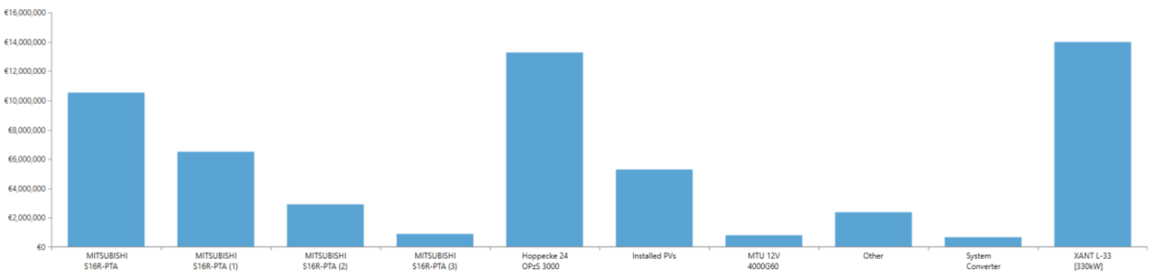


Figure 64. Net Present Cost Summary by component for Scenario 5

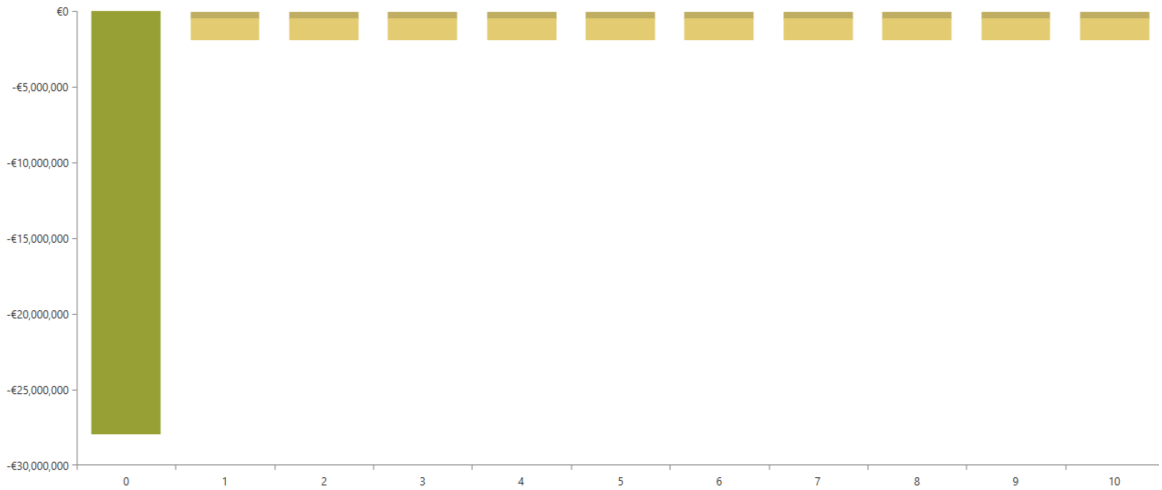


Figure 65 . Cash flow for Scenario 5

4.7 Scenario 6

In scenario 6, a combination of XANT L-33 and Vestas V82 wind turbines will be installed with the existing diesel generators. The aim of this set up is to reduce the use of diesel fuel. The search space of Vestas V82 will be 0-1 and the search space of XANT L-33 will between 0 and 5. This set up is considered because of the difficulty of V82 installation. The considerably easier installation of XANT L-33 is the reason of the wider search space. The battery storage will be expanded to n_{day}=4 to accommodate the higher wind power penetration.

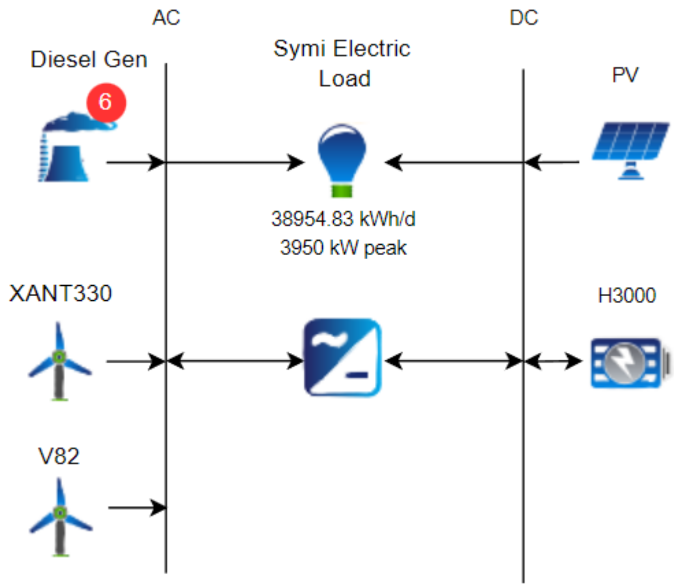


Figure 66. Scenario 6 used for simulation in HOMER

The architecture result HOMER output are the shown in table 51. This scenario has the biggest excess electricity studied till now with 9.72%. This excess electricity will need a massive increase of battery capacity to be decreased. The results of the excess electricity production compared to the load are show in figure #.

System	PV(kW)	XANT330	Vestas V82	S16R-PTA G1	S16R-PTA G2(kW)	S16R-PTA G3(kW)	S16R-PTA G4(kW)	MTU 12V	H3000	Converter (kW)	Excess Elec.(%)
Scenario 5	3,200	5	1	900	900	900	900	700	9,024	2,222	4.65

Table 51 . HOMER PRO Optimised Architecture for scenario 6

More specifically each component is presented in the table below :

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
MITSUBISHI S16R-PTA G1	1,069,152	5.79	520	247,732	2,056
MITSUBISHI S16R-PTA G2	602,676	3.26	470	139,780	1,282
MITSUBISHI S16R-PTA G3	305,830	1.66	423	71,011	723
MITSUBISHI S16R-PTA G4	1,069,152	0.864	299	31,664	454
Vestas V82[1650 Kw]	7,665,893	41.5	176	28,306	537
XANT L-33 [330kW]	3,656,080	19.8	728	-	7,194
Installed PVs	5,179,126	28.0	592	-	4,386
System	18,478,757	100			

Table 52. HOMER PRO component details for scenario 6

Unlike any other scenario, the load requirement the is met by mainly by wind turbines with a 61.3%.The system manages to achieve a renewable fraction of 86%. In this scenario, the diesel generators decrease by two and they are used to supplement energy required mainly during peak months. Conventional diesel generators account for only 10.71% of total output, the scenario with the least diesel contribution. Figure # shows the monthly electrical generation of each component.

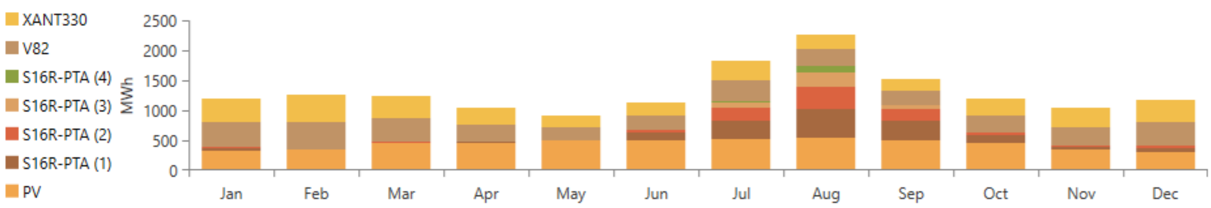


Figure 67 . Monthly Electrical Production of Scenario 6

In this case, it is to be expected that Photovoltaics will remain about the same as scenario 5, since the set up is exactly the same . Figure 68 and Table 53 depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 3200 kW with a maximum power output of 2,805 kW.The total hours of operation of PV panels remains the same, which is to be expected at 4386 h/year.

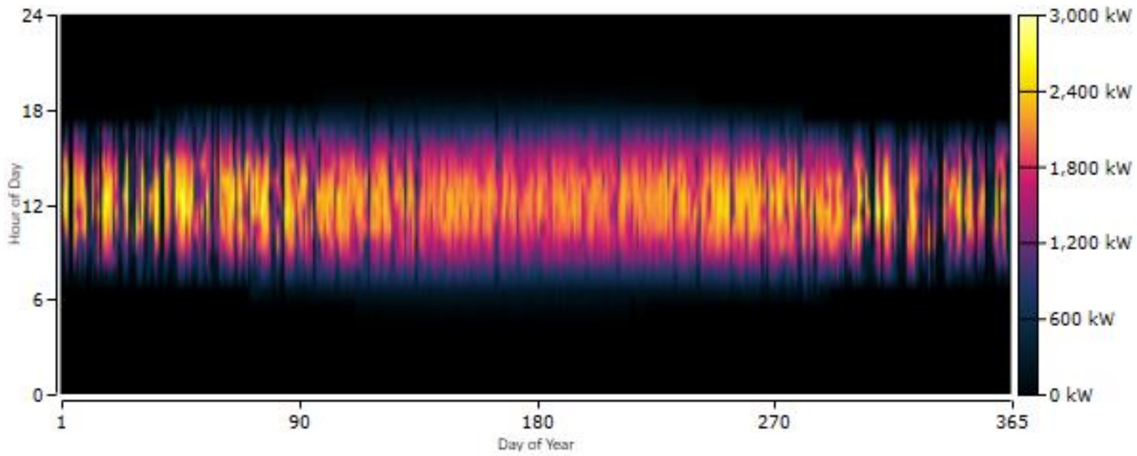


Figure 68 . Hourly PV Power Production of Scenario 6.

Quantity	Value	Units
Rated Capacity	3,200	kW
Mean Output	591	kW
Mean Output	14,189	kWh/d
Capacity Factor	18.5	%
Total Production	5,179,126	kWh/yr
Minimum Output	0	kW
Maximum Output	2,805	kW
PV Penetration	36.4	%
Hours of Operation	4,386	hrs/yr

Levelized Cost	0.0679	€/kWh

Table 53. Solar PV simulation Results of scenario 6

Figure 70 depict the hourly output power of XANT L-33, like scenario 5. Table 54 depicts the electricity simulation results. Unlike solar production electricity generation is maximized during the winter season, with February having the largest average production .From the summer months, July has the largest energy production. The total rated capacity of the XANT L-33 in this scenario is 3,300 kW with a maximum power output of 3,390 kW.The total hours of operation of the wind turbines amount to 7,227 hrs/yr or 19 hours per day.

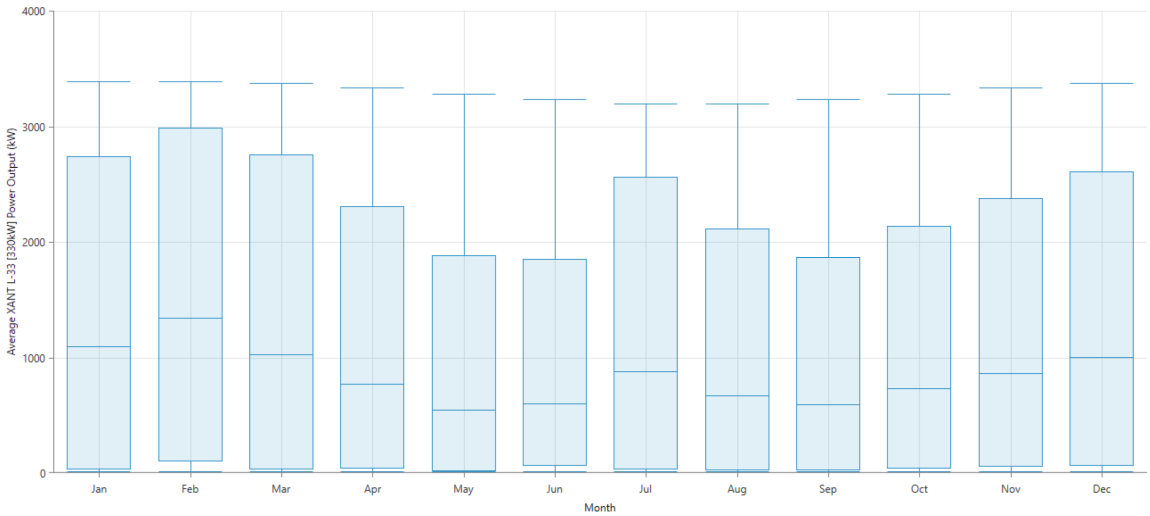


Figure 69. Monthly Power Output Average of XANT L-33 in scenario 6

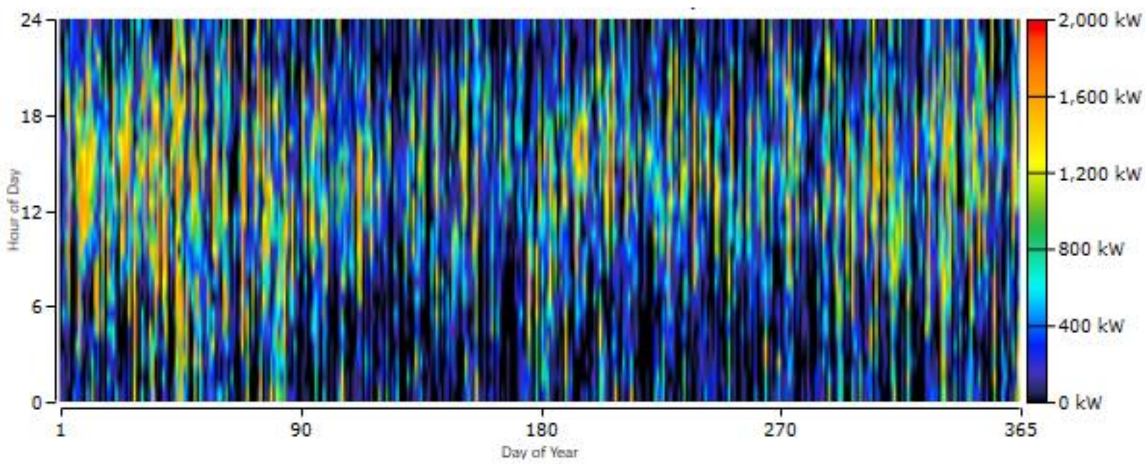


Figure 70. Hourly Wind Turbine Power output of XANT L-33 in Scenario 6

Quantity	Value	Units
Total Rated Capacity	1,650	kW
Mean Output	417	kW
Capacity Factor	25.3	%
Total Production	3,656,080	kWh/yr
Minimum Output	0	kW
Maximum Output	1,696	kW
Wind Penetration	25.7	%
Hours of Operation	7,227	hrs/yr
Levelized Cost	0.125	€/kWh

Table 54. Xant L-33 simulation Results of scenario 6

Figure 72 depict the hourly output power of Vestas V82, like scenario 4. Table 55 depicts the electricity simulation results. Electricity generation is maximized during the winter season, with February having the largest average production .From the summer months, July has the largest energy production. The total rated capacity of the Vestas V82 in this scenario is 3,300 kW with a maximum power output of 3,390 kW.The total hours of operation of the wind turbines amount to 7,313 hrs/yr or 19 hours per day.

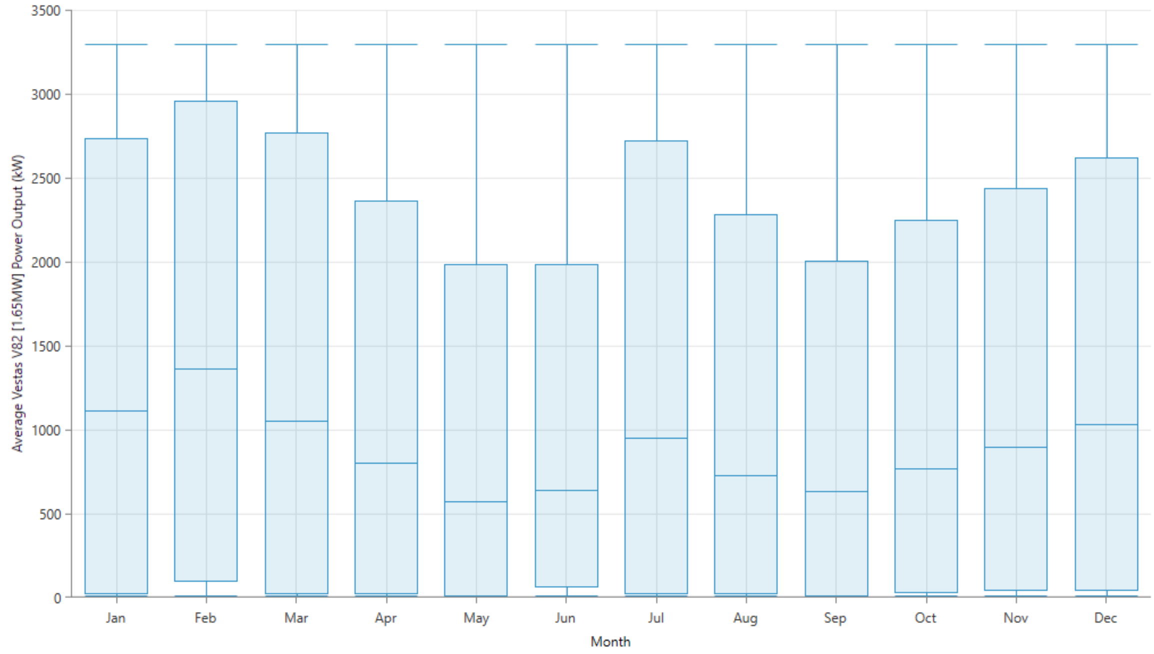


Figure 71. Monthly Power Output Average of Vestas V82 in scenario 6

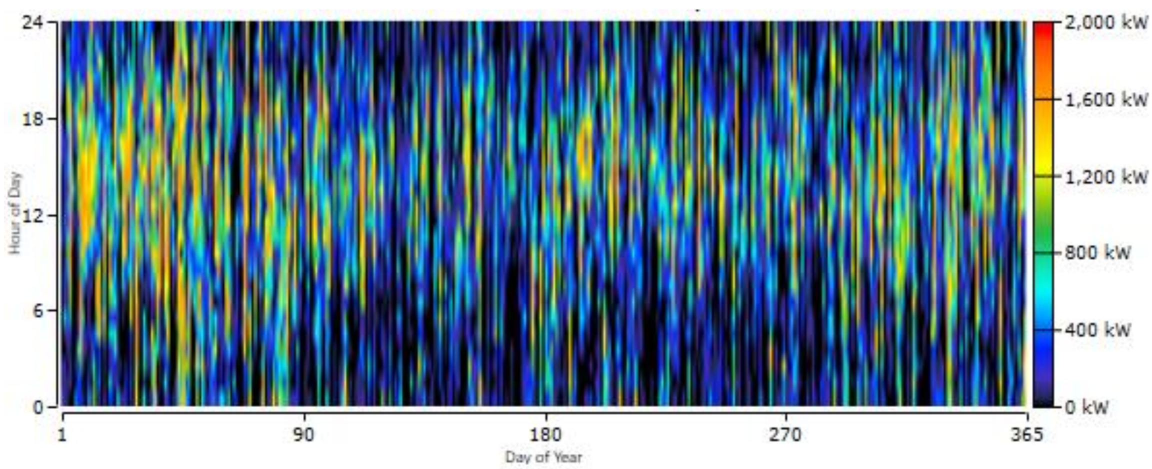


Figure 72. Hourly Wind Turbine Power output of Vestas V82 in Scenario 6

Quantity	Value	Units
Total Rated Capacity	1,650	kW
Mean Output	438	kW
Capacity Factor	26.5	%

Total Production	3,832,946	kWh/yr
Minimum Output	0	kW
Maximum Output	1,650	kW
Wind Penetration	27.0	%
Hours of Operation	7,313	hrs/yr
Levelized Cost	0.125	€/kWh

Table 55. Vestas V82 simulation Results of scenario 6

In this scenario the storage bank is enlarged to n_{day}=4 and is consisted Hoppecke 24 OPzS 3000 lead acid batteries. Observing the state of charge frequency from Figure # below,that the batteries remain at a depth-of-charge of 30% with a frequency of 15.48% and at depth-of-charge of 100% with a frequency of 18.96%. This is the first scenario where the batteries have a higher frequency at 100% charge state than 30%. The results of simulations of battery schemes are shown in Table 19. the results of which are presented in the table below:

Quantity	Value	Units
Batteries	9,024	qty.
String Size	12.0	batteries
Strings in Parallel	752	strings
Bus Voltage	24.0	V
Autonomy	27.8	hr
Storage Wear Cost	0.156	€/kWh
Nominal Capacity	64,515	kWh
Usable Nominal Capacity	45,161	kWh
Lifetime Throughput	34,075,952	kWh
Expected Life	10.0	yr
Average Energy Cost	0	€/kWh
Energy In	3,638,194	kWh/yr
Energy Out	3,160,074	kWh/yr
Storage Depletion	33,672	kWh/yr
Losses	511,793	kWh/yr
Annual Throughput	3,407,595	kWh/yr

Table 56. Storage simulation Results of scenario 6

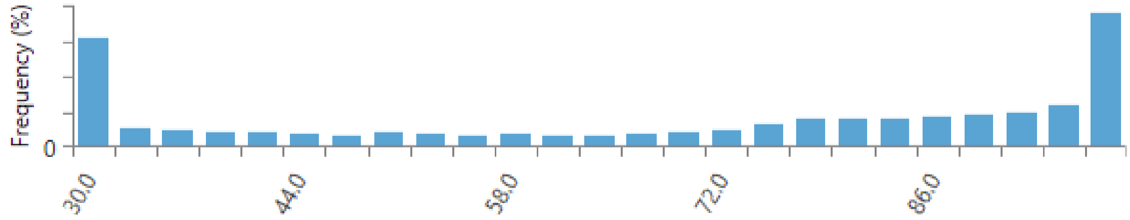


Figure 73. Hoppecke 24 OPzS 3000 state of charge frequency of Scenario 6.

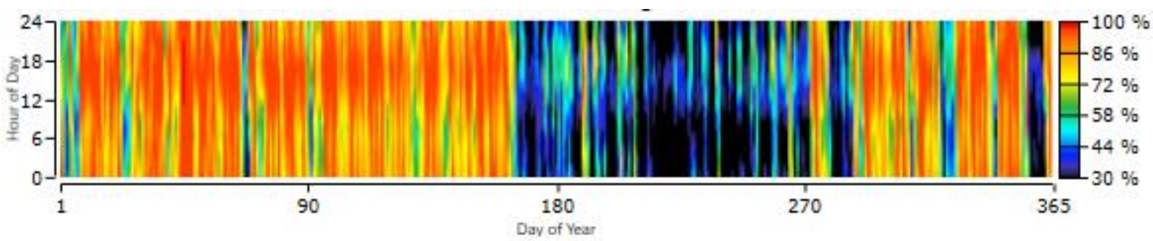


Figure 74. Hoppecke 24 OPzS 3000 state of charge of Scenario 6.

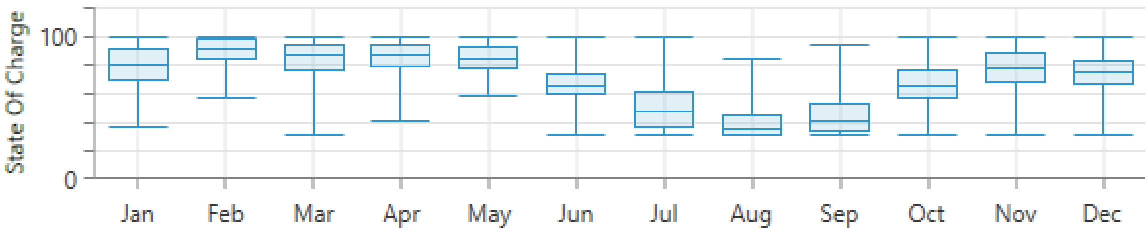


Figure 75. Hoppecke 24 OPzS 3000 monthly average state of charge of Scenario 6.

Excess electricity is observed during all months except August. Most excess electricity is observed during February when wind power output is maxized, with an average excess electricity of 326.04 kW. Least excess electricity is observed during September with an average of 13.75 kW.

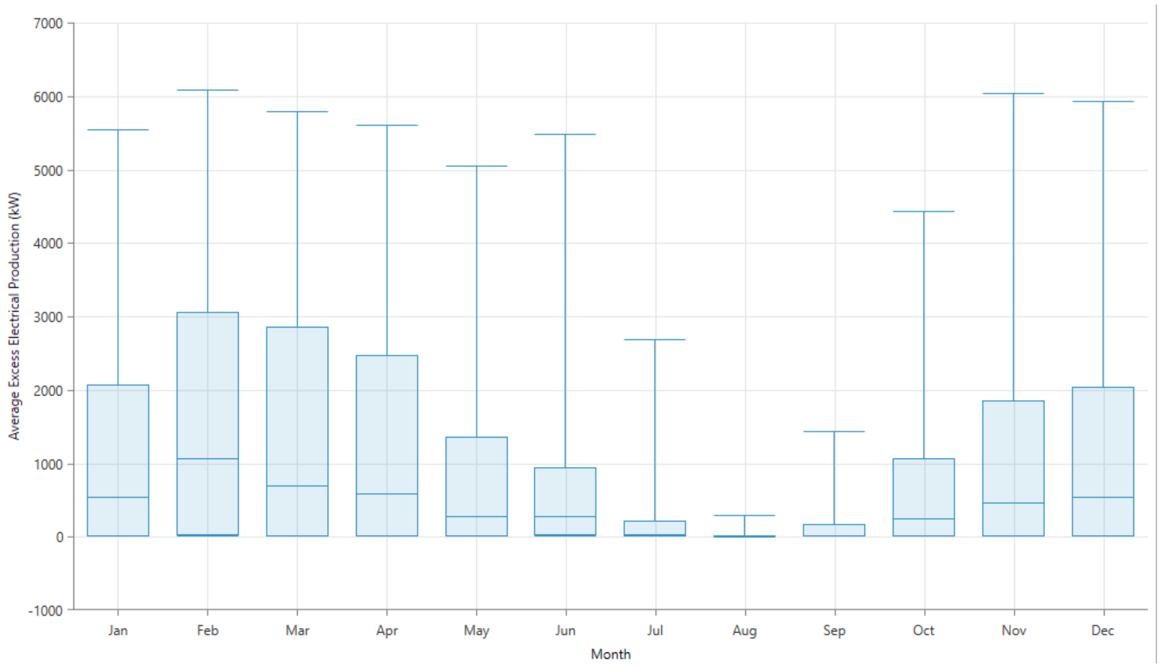


Figure 76. Monthly average excess electrical production of Scenario 6

Economic Characteristic of Scenario 6:

In scenario 6, it is to be expected that the capital required will be larger than scenario 4 and 5, that's because five XANT L-33 and two vestas V82 are used in this scenarion.The costs of fuel come up at 874,861.884€/year the lowest than any other scenario. It shall also be noticed that the renewable penetration rose to 86% .

Total fuel consumed	**726,086**	**L**
Avg fuel per day	1,989	L/day
Avg fuel per hour	82.9	L/hour

Table 57. Yearly fuel consumption Results of scenario 6

The economic aspects for the system are presented in Table 58.

Scenario	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(L/yr)
Scenario 6	€55,983,807	€0.2613	1,858,909	€27,971,715.00	78.2%	726,086

Table 58. System results for scenario 6

Component	Capital(€)	O&M(€)	Fuel(€)	Total(€)
MITSUBISHI S16R-PTA	€0.00	€0.00	€10,237,063.28	€10,237,063.28
MITSUBISHI S16R-PTA (1)	€0.00	€0.00	€6,222,876.87	€6,222,876.87
MITSUBISHI S16R-PTA (2)	€0.00	€0.00	€2,785,876.92	€2,785,876.92
MITSUBISHI S16R-PTA (3)	€0.00	€0.00	€843,640.54	€843,640.54
MTU 12V 4000G60	€0.00	€0.00	€786,859.47	€786,859.47
Hoppecke 24 OPzS 3000	€13,175,040.00	€679,917.84	€0.00	€13,854,957.84
Installed PVs	€4,480,000.00	€819,759.09	€0.00	€5,299,759.09
Other	€0.00	€1,449,468.90	€0.00	€2,295,279.26
System Converter	€666,675.00	€666,675.00	€0.00	€666,675.00
Vestas V82 [1.65MW]	€4,550,000.00	€1,537,048.30	€0.00	€6,087,048.30
XANT L-33 [330kW]	€5,100,000.00	€1,803,771.39	€0.00	€6,903,771.39
System	€27,971,715.00	€7,135,775.88	€20,876,317.09	€55,983,807.97

Table 59. Analysis of system costs for scenario 6

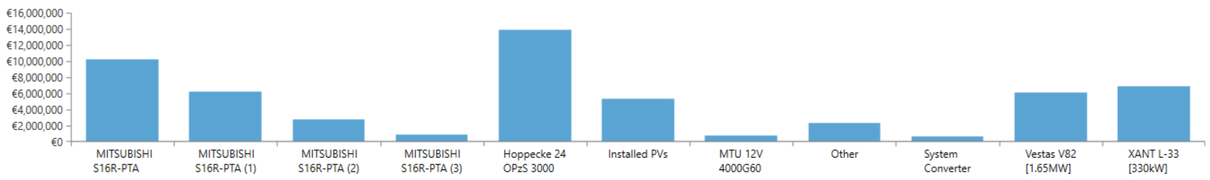


Figure 76. Net Present Cost Summary by component for Scenario 6.

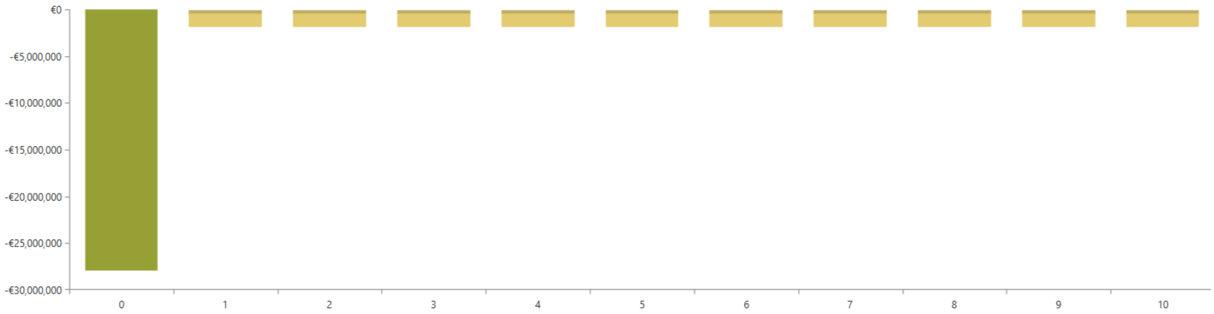


Figure 77. Cash flow for Scenario 6.

4.8 Scenario 7

In scenario 7, a system with 100% renewable energy penetration will be simulated. This is the first scenario where the solar phovoltaic search space will be expanded to 3,200-4,200-5,600-6,400 kW. The search space of Vestas V82 will between 0 to 3 and the search space of XANT L-33 will between 0 and 6. This set up is considered to test the feasibility of a totally fuel independent system. The considerably easier installation of XANT L-33 is the reason of the wider search space. The battery storage will be expanded to n_{day}=7 to accommodate the renewable power penetration.

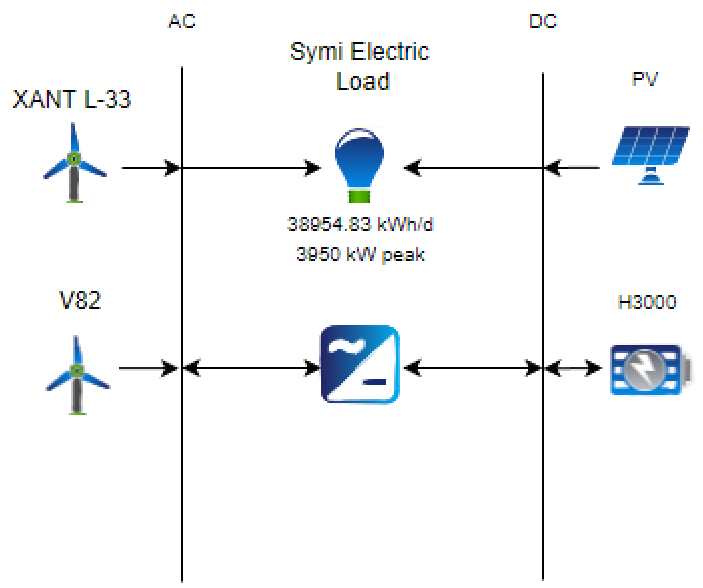


Figure 77. Scenario 7 used for simulation in HOMER

The architecture result HOMER output are the shown in table #. This scenario has the biggest excess electricity with 42.6%. This excess electricity shows how oversized the current system is in order to cover loads when renewable energy output is low . This excess electricity can not be covered by battery storage because the costs would be massive. The results of the excess electricity production compared to the load are show in figure #.

System	PV(kW)	XANT330	Vestas V82	H3000	Converter (kW)	Excess Elec.(%)
Scenario 7	6,400	3	6	15,576	4,074	42.6

Table 60 . HOMER PRO Optimised Architecture for scenario 7

More specifically each component is presented in the table below :

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
Vestas V82[1650 Kw]	10,358,252	39.7	1,298	-	7,227
XANT L-33 [330kW]	11,372,722	43.5	1,298	-	7,227
Installed PVs	4,387,296	16.8	1,182	-	4,386
System	26,118,270	100			

Table 61. HOMER PRO component details for scenario 7

This is the first scenario which electrical production is 100% met by renewable energy sources. Monthly Electrical Production is depicted in the figure # below.

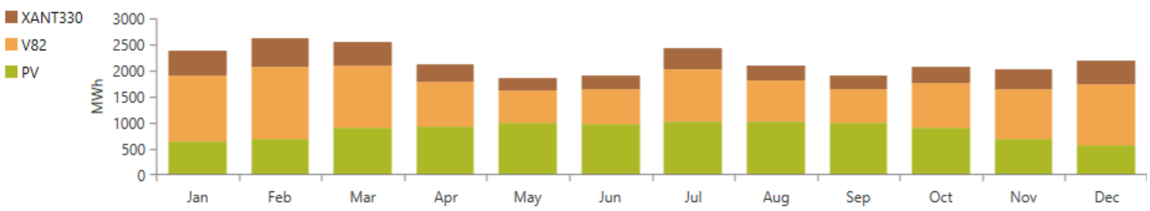


Figure 78. Monthly Electrical Production of Scenario 7.

It is the first scenario which Photovoltaics are expanded. Figure 79 and Table 62 depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 6400 kW with a maximum power output of 5,610kW.The total hours of operation of PV panels remains the same, which is to be expected at 4386 h/year.

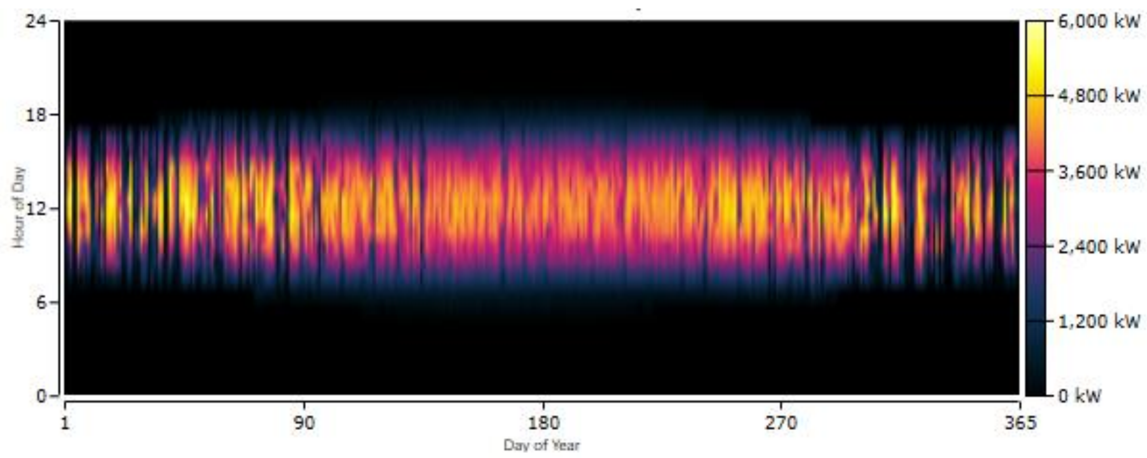


Figure 79 . Hourly PV Power Production of Scenario 7.

Quantity	Value	Units
Rated Capacity	6,400	kW
Mean Output	1,182	kW
Mean Output	28,379	kWh/d
Capacity Factor	18.5	%
Total Production	10,358,252	kWh/yr
Minimum Output	0	kW
Maximum Output	5,610	kW
PV Penetration	72.9	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0679	€/kWh

Table 62. HOMER PRO component details for scenario 6

Figure 81 depict the hourly output power of XANT L-33. Table 63 depicts the electricity simulation results. Unlike solar production electricity generation is maximized during the winter season, with February having the largest average production .From the summer months, July has the largest energy production. The total rated capacity of the XANT L-33 in this scenario is 1,980 kW with a maximum power output of 2,035 kW.The total hours of operation of the wind turbines amount to 7,227 hrs/yr or 19 hours per day.

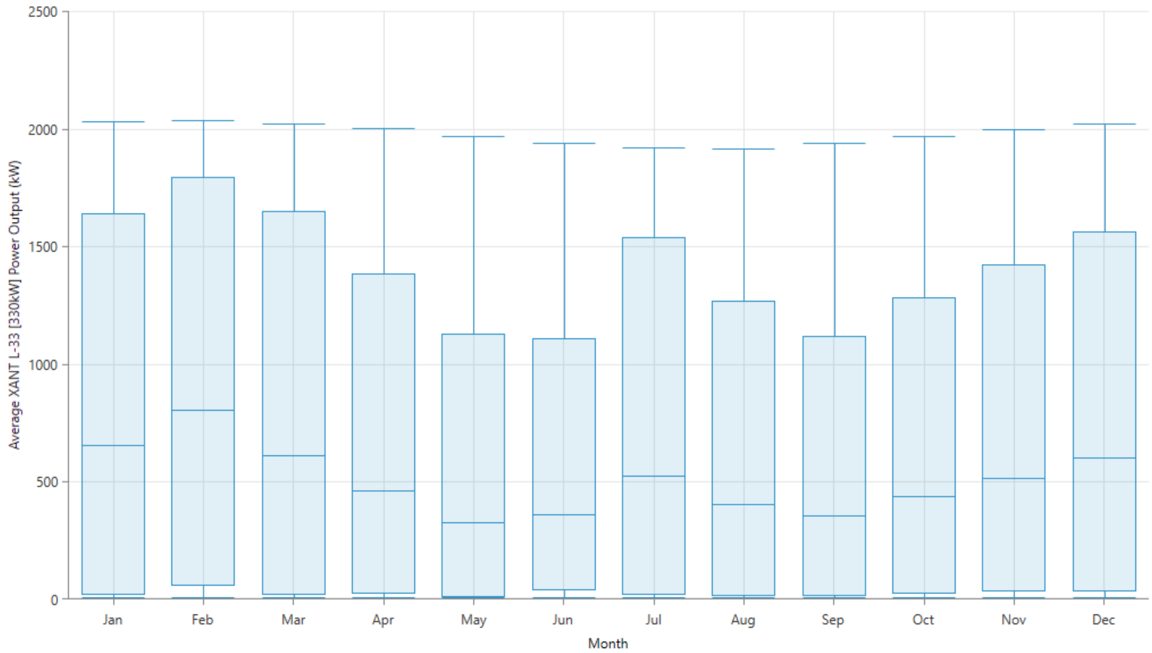


Figure 80 . Monthly Power Output Average of XANT L-33 in scenario 8.

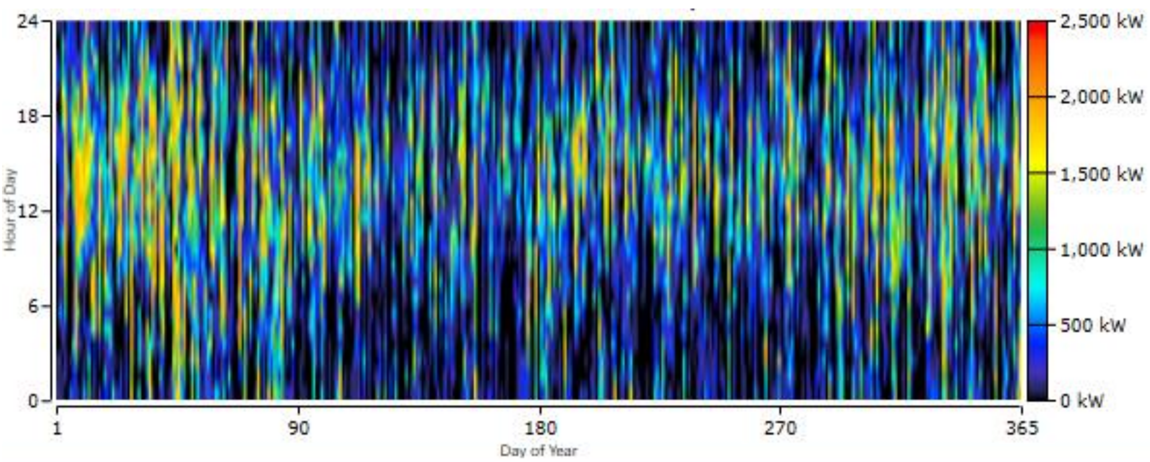


Figure 81 . Hourly Wind Turbine Power output of XANT L-33 in Scenario 8.

Quantity	Value	Units
Total Rated Capacity	1,980	kW
Mean Output	501	kW
Capacity Factor	25.3	%
Total Production	4,387,296	kWh/yr
Minimum Output	0	kW
Maximum Output	2,035	kW
Wind Penetration	30.9	%
Hours of Operation	7,227	hrs/yr
Levelized Cost	0.125	€/kWh

Table 63. Xant L-33 simulation Results of scenario 7

Figure 83 depict the hourly output power of Vestas V82. Table 64 depicts the electricity simulation results. Electricity generation is maximized during the winter season, with February having the largest average production .From the summer months, July has the largest energy production. The total rated capacity of the Vestas V82 in this scenario is 3,300 kW with a maximum power output of 3,390 kW.The total hours of operation of the wind turbines amount to 7,313 hrs/yr or 19 hours per day.

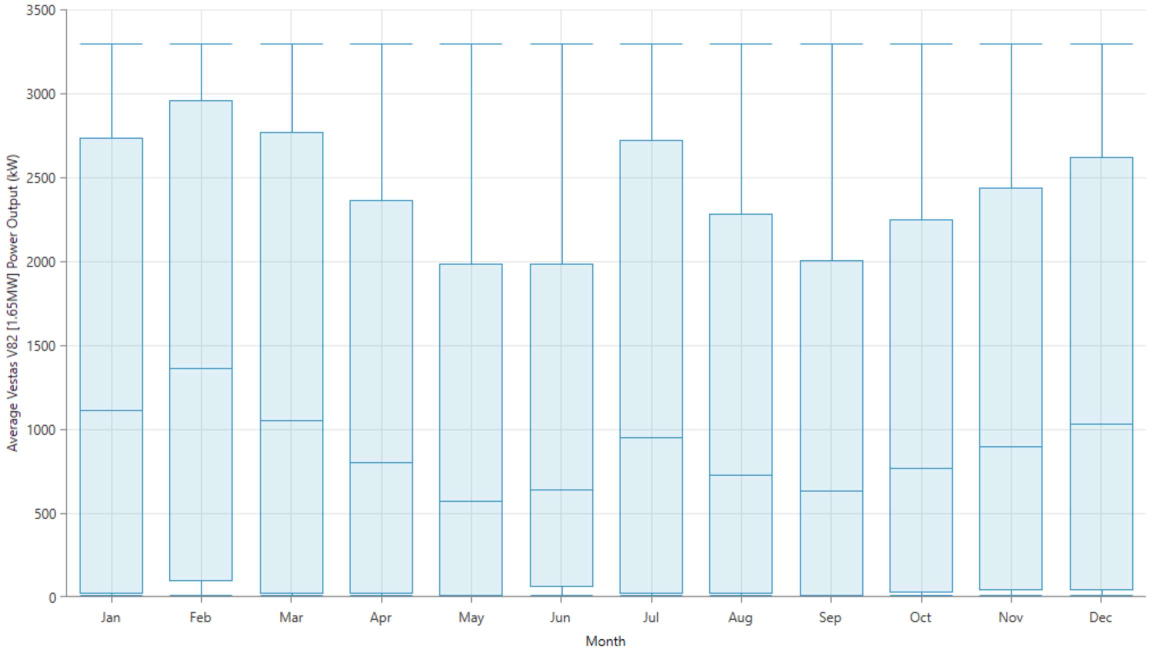


Figure 82 . Monthly Power Output Average of Vestas V82 in scenario 7.

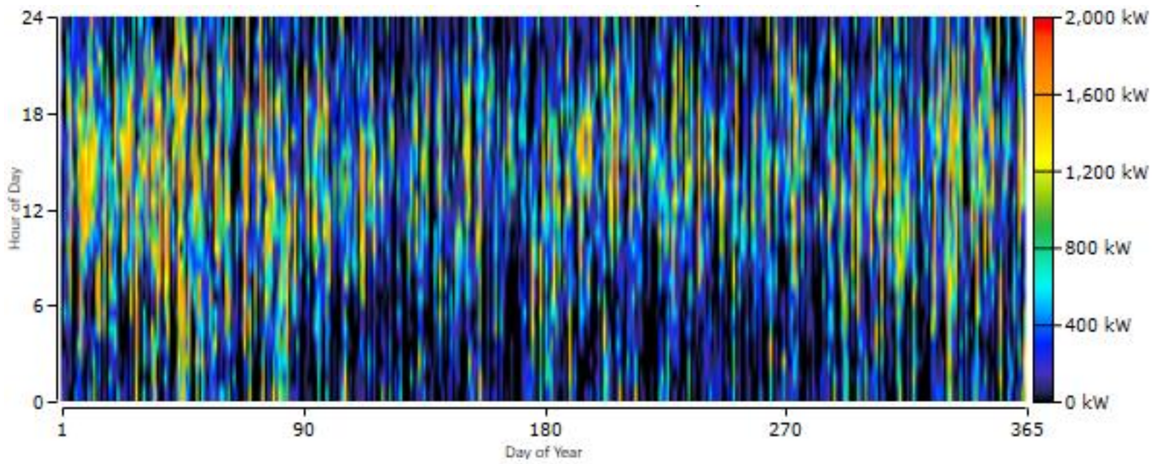


Figure 83 . Hourly Wind Turbine Power output of Vestas V82 in Scenario 7.

Quantity	Value	Units
Total Rated Capacity	4,950	kW
Mean Output	1,298	kW
Capacity Factor	26.2	%
Total Production	11,372,722	kWh/yr
Minimum Output	0	kW
Maximum Output	5,012	kW
Wind Penetration	80.0	%
Hours of Operation	7,313	hrs/yr
Levelized Cost	0.107	€/kWh

Table 64. Xant L-33 simulation Results of scenario 7

In this scenario the storage bank is enlarged to n_{day}=7 and is consisted Hoppecke 24 OPzS 3000 lead acid batteries. Observing the state of charge frequency from Figure 84 below,that the batteries remain at a depth-of-charge of 30% with a frequency of 2.15% and at depth-of-charge of 100% with a frequency of 45.19%. This is extreme difference is the result of the oversized system, but it is needed to cover umet load demand. The results of simulations of battery schemes are shown in Table the results of which are presented in the table below:

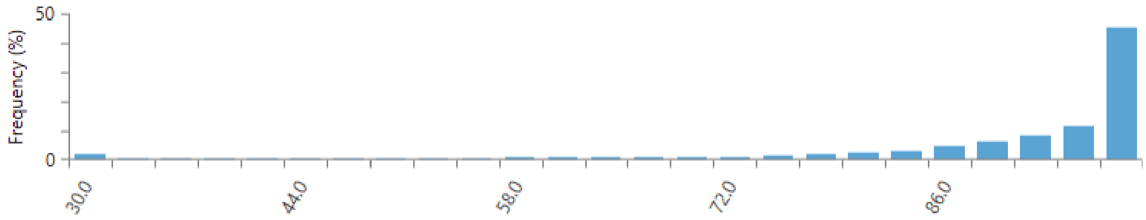


Figure 84 . Hoppecke 24 OPzS 3000 state of charge frequency of Scenario 7.

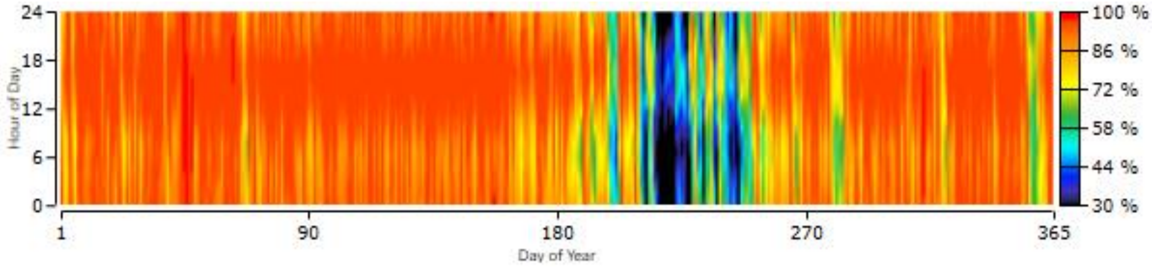


Figure 85 . Hoppecke 24 OPzS 3000 state of charge of Scenario 7.

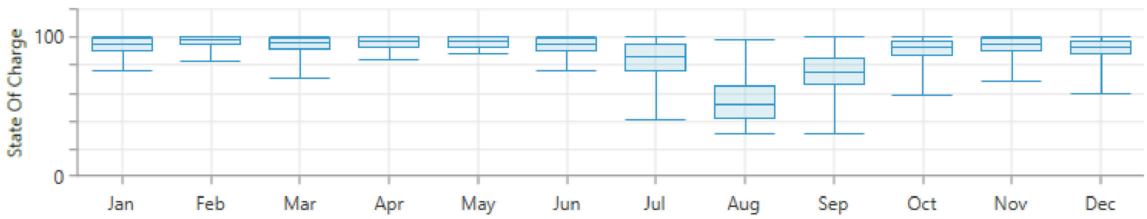


Figure 86 . Hoppecke 24 OPzS 3000 monthly average state of charge of Scenario 7.

Quantity	Value	Units
Batteries	15,576	qty.
String Size	12.0	batteries
Strings in Parallel	1,298	strings
Bus Voltage	24.0	V
Autonomy	48.0	hr
Storage Wear Cost	0.156	€/kWh
Nominal Capacity	111,357	kWh
Usable Nominal Capacity	77,950	kWh
Lifetime Throughput	44,764,008	kWh

Expected Life	10.0	yr
Average Energy Cost	0	€/kWh
Energy In	4,822,402	kWh/yr
Energy Out	4,151,243	kWh/yr
Storage Depletion	4,289	kWh/yr
Losses	675,448	kWh/yr
Annual Throughput	4,476,401	kWh/yr

Table 65. Storage simulation Results of scenario 7

Excess electricity is observed during all months. Most excess electricity is observed during February when wind power output is maxized, with an average excess electricity of 2432.98 kW. Least excess electricity is observed during August with an average of 2 kW.

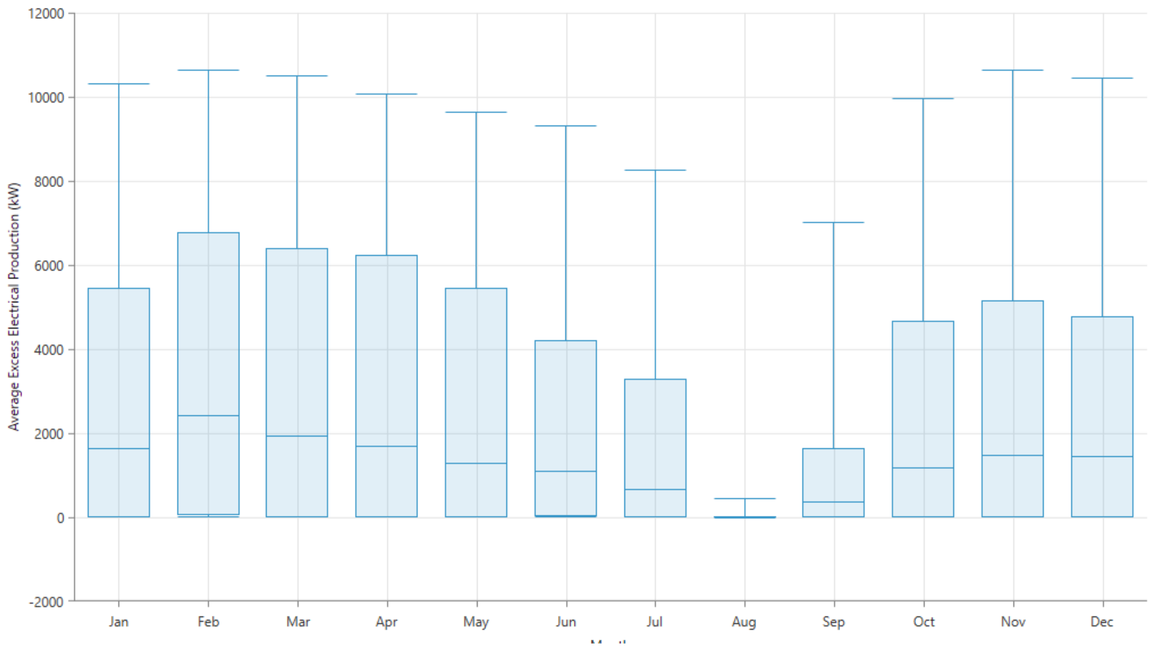


Figure 87 . Monthly average excess electrical production of Scenario 7.

Economic Characteristic of Scenario 7:

Scenario	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(L/yr)
Scenario 7	€62,281,970	€0.2969	€636,320	€52,693,197.50	100%	0

Table 66. System results for scenario 7

Component	Capital(€)	O&M(€)	Fuel(€)	Total(€)
Hoppecke 24 OPzS 3000	€22,740,960.00	€0.00	€1,173,581.59	€23,914,541.59
Installed PVs	€8,960,000.00	€0.00	€1,639,518.19	€10,599,518.19
System Converter	€1,222,237.50	€0.00	€0.00	€1,222,237.50
Vestas V82 [1.65MW]	€13,650,000.00	€0.00	€4,611,144.91	€18,261,144.91
XANT L-33 [330kW]	€6,120,000.00	€0.00	€2,164,525.67	€8,284,525.67
System	€52,693,197.50	€0.00	€9,588,770.35	€62,281,967.85
Hoppecke 24 OPzS 3000	€22,740,960.00	€0.00	€1,173,581.59	€23,914,541.59

Table 67. Analysis of system costs for scenario 7

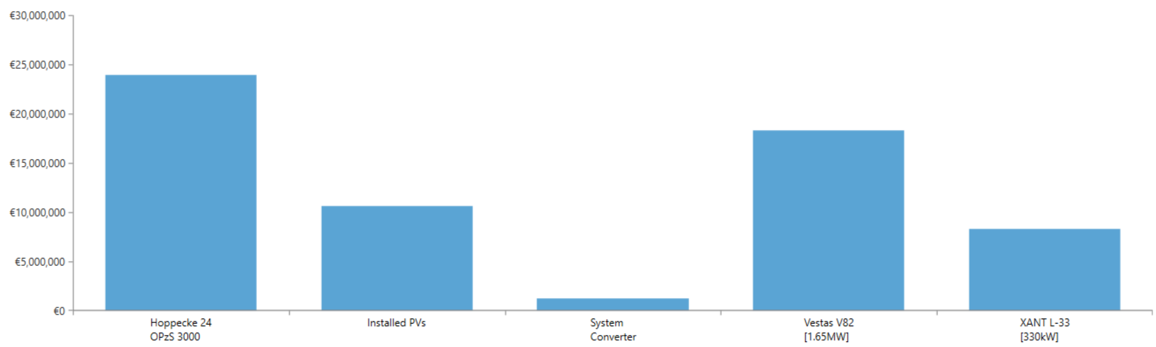


Figure 89 . Net Present Cost Summary by component for Scenario 7.

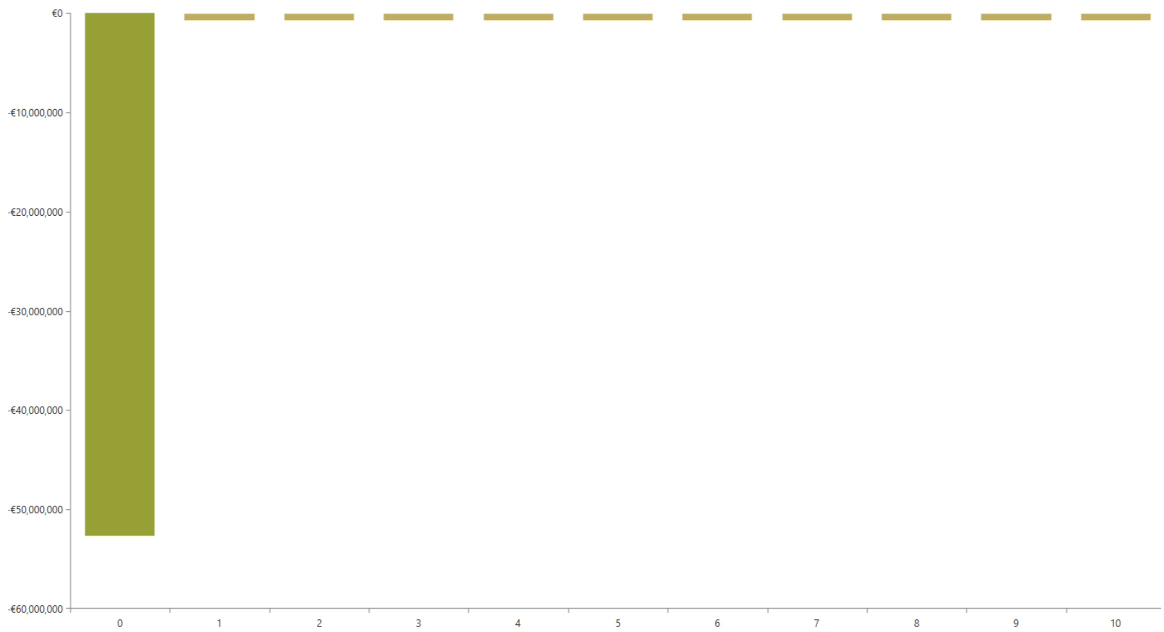


Figure 90. Cash flow for Scenario 7.

4.9 Scenario 8

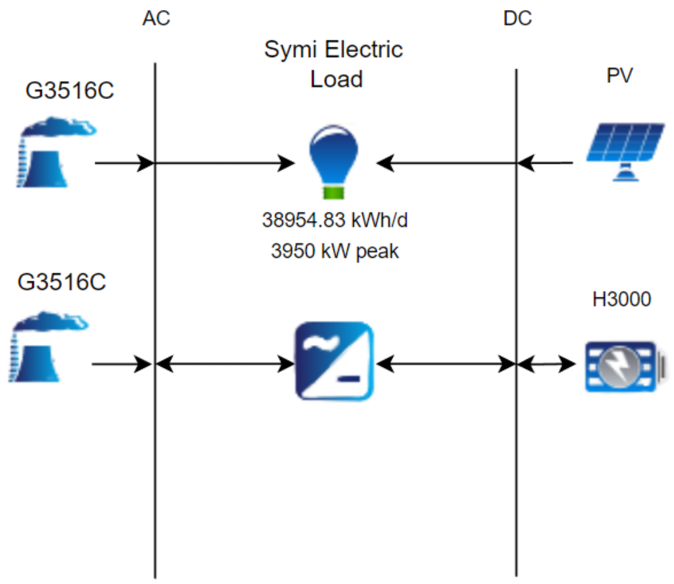


Figure 91. Scenario 8 used for simulation in HOMER

In this scenario the option of replacing all old diesel genators with new Natural-Gas operated ones is tested. The hybrid system in Scenario 8 consists of the same amount of solar panels and natural gas generators which replaced the diesel generators. Two generators are selected. Unfortunately installing natural gas generators would also require a storage facility for natural gas and a regasification plant. The costs of those is calculated at 12,000,000€. Due to the recent volatile nature of Natural gas, sensetivity analysis will be made in this scenario. Prices of july 2020,January 2021,July 21,January 2022 and July 2022 will be taken into account. The prices of m^3 of Natural gas are depicted in the table below.

july 2020	0.1 €/ m^3
January 2021	0.2 €/ m^3
July 21	0.35 €/ m^3
January 2022	1.21 €/ m^3
July 2022	1.34 €/ m^3

Table 68. Natural gas cost throughout two years

After optimization, the configuration depicted in the table below is the ideal system. The renewable percentage for this example remains low, at 2.05 percent, like the base scenario. The reduction of excess electricity is not the primary goal in this scenario because excess electricity should be 0% as in the base case since the load is served from generators and not renewables. The NPC, the LCoE, and the quantity of conventional units should be the primary optimization targets.

The results HOMER pro produces for optimised electricity generation are shown in table # below.

System	PV(kW)	G3516C G1	G3516C G2	Converter	Excess Elec.(%)
Scenario 8	190	2,000	2,000	148	0

Table 69 . HOMER PRO Optimised Architecture for scenario 8

More specifically for each component is presented in the table below:

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption m^3/year	Operational Hours h/year
CAT-NG-2500kVA-50Hz-CP G1	4,170,496	29.3	1.337	1,658,477	4,288
CAT-NG-2500kVA-50Hz-CP G2	9,762,987	68.6	1,279	1,588,711	8,760
PV	307,511	2.16	318	81,859	4,386
Total	14,241,343	100	-	3,466,824	17,434

Table 70. HOMER PRO component details for scenario 8

From the above table it can be noticed that generator G2 was running all year round with G1 providing peak load demands during non peak months and providing most electricity during July and August.

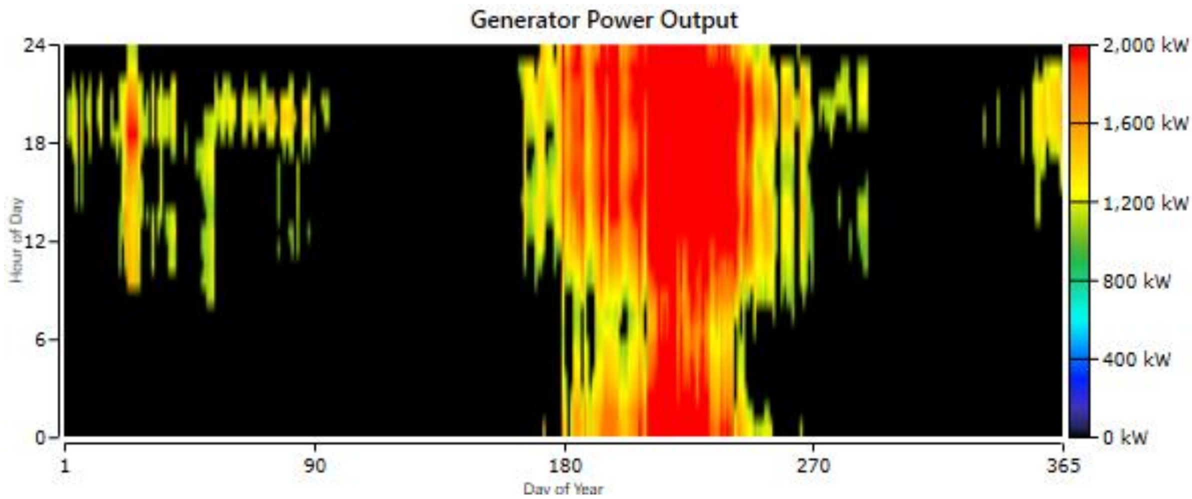


Figure 92 . Yearly generator power output G1 for Scenario 8.

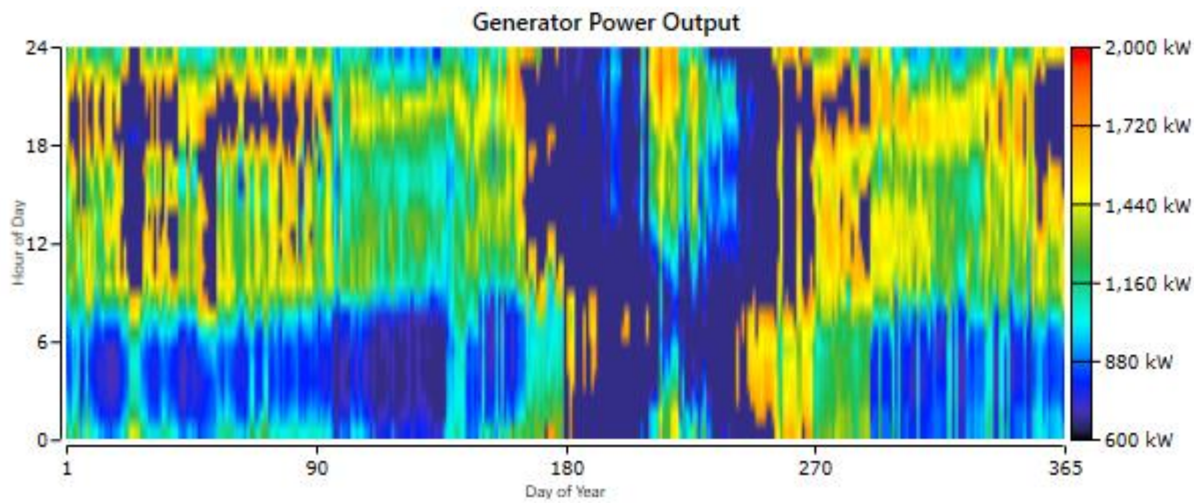


Figure 93 . Yearly generator power output G2 for Scenario 8.

The system yearly consumes 3,466,824 m^3 of natural gas with an average of 9,498 m^3/day or 396 m^3/hour.

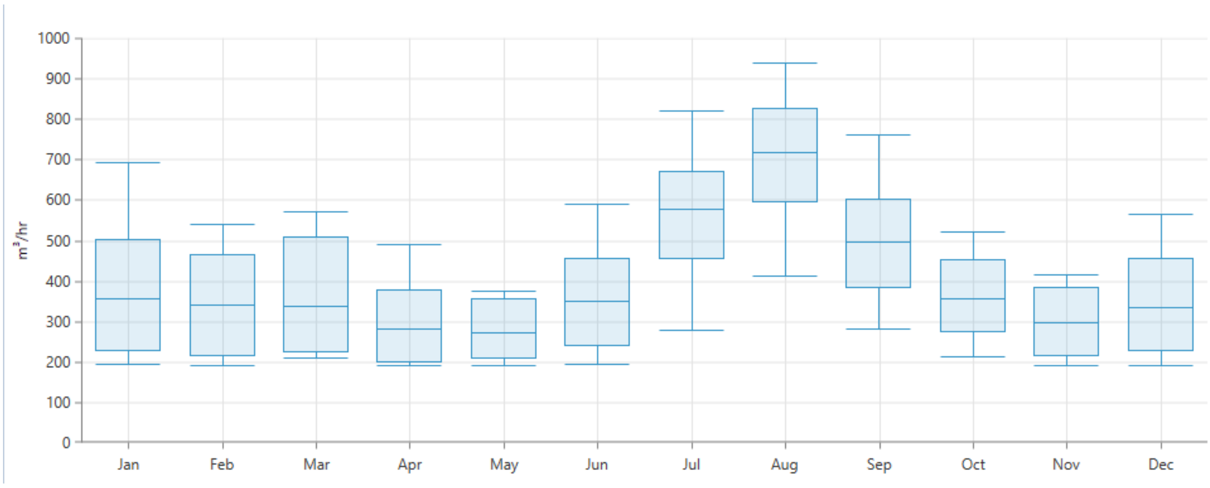


Figure 94 . Yearly fuel consumption for Scenario 8.

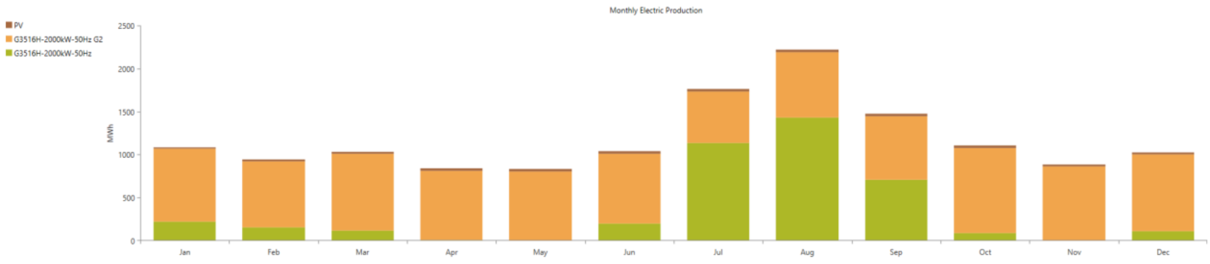


Figure 95. Monthly Electrical Production of Scenario 8.

Because the installation of PV arays has not changed from the base scenario, it is to be expected that Photovoltaics will not affect the system costs by any big margin. Figure and Table depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 190 kW with a maximum power output of 167 kW.The total hours of operation of PV panels is 4386 h/year which is about 12 hours per day.

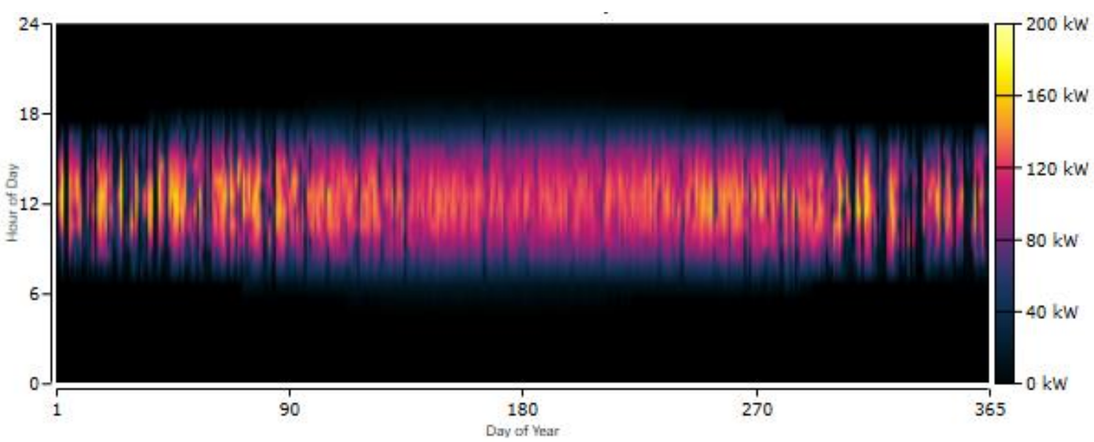


Figure 96. Hourly PV Power Production of Scenario 8.

Quantinty	Value	Units
Rated Capacity	0	kW
Mean Output	167	kW
Mean Output	2.17	kWh/d
Capacity Factor	4,386	%
Total Production	0.0678	kWh/yr
Minimum Output	0	kW
Maximum Output	167	kW
PV Penetration	2.17	%
Hours of Operation	4,386	Hrs/yr
Levelized Cost	0.0678	€/kWh

Table 71. HOMER PRO PV results for scenario 8

Economic Results of Scenario 8

Following the system costs, the economic aspects for the base system are presented in Table # . It is noticed that the huge cost of the selected configuration is the fuel costs similarly to base scenario. Natural gas prices for the year 2022 have rosen to prices seen in 2008. Those costs lead this system to have a fuel cost value of € 1,740,128.8€/year. The yearly decrease in fuel costs is very impressive compared to base scenario and the initial capital provided for the generator acquisition would be recovered fast. Unfortunately a complete picture of this set up can not be acquired because the cost of natural gas storing facility is not included in those costs.

Sensetivity €/m^3	NPC	COE	Operating Cost	Initial Capital	Renewable Fraction	Total Fuel(m^3/yr)
0.100	27,156,150€	0.1292€	888,206€	14,294,34€	2.05%	3,466,824
0.200	32,903,000€	0.1536€	1,234,888€	14,294,34€	2.03%	3,466,824
0.350	40,739,290€	0.1901€	1,754,912€	14,294,34€	2.03%	3,466,824
1.21	85,657,160€	0.3998€	4,735,214€	14,294,34€	2.03%	3,466,824
1.34	92,446,940€	0.4315€	5,185,790€	14,294,34€	2.03%	3,466,824

Table 72. HOMER PRO sensetivity results for scenario 8

From table # it is noticed that the cost of the this scenario has increased dramatically compared to 2020. The comparison for this scenario will happen with the latest price available, meaning 1.34 €/ m^3.

Componen t	Capital	Replaceme nt	O&M	Fuel	Total
CAT-NG-2500kVA-50Hz-CP	€12,995,652	€0.00	€0.00	€20,380,304.70	€33,375,956.70
CAT-NG-2500kVA-50Hz-CP G2	€995,652	€0.00	€0.00	€49,606,606.59	€50,602,258.59
Installed PVs	€266,000	€0.00	€48,673.20	€0.00	€314,673.20
Other	€0.00	€0.00	€8,109,150.12	€0.00	€8,109,150.12
System Converter	€44,445	€0.00	€0.00	€0.00	€44,445.00
System	€14,301,749.00	€0.00	€8,157,823.32	€69,986,911.30	€92,446,483.61

Table 73. Analysis of system costs for scenario 8

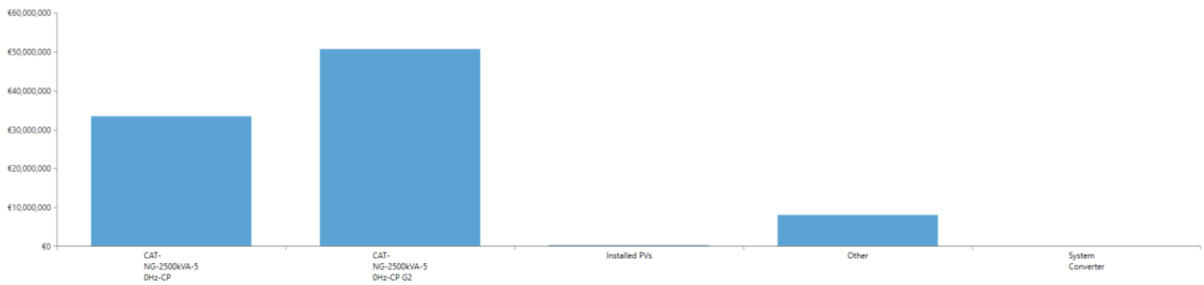


Figure 97 . Net Present Cost Summary by component for Scenario 8.

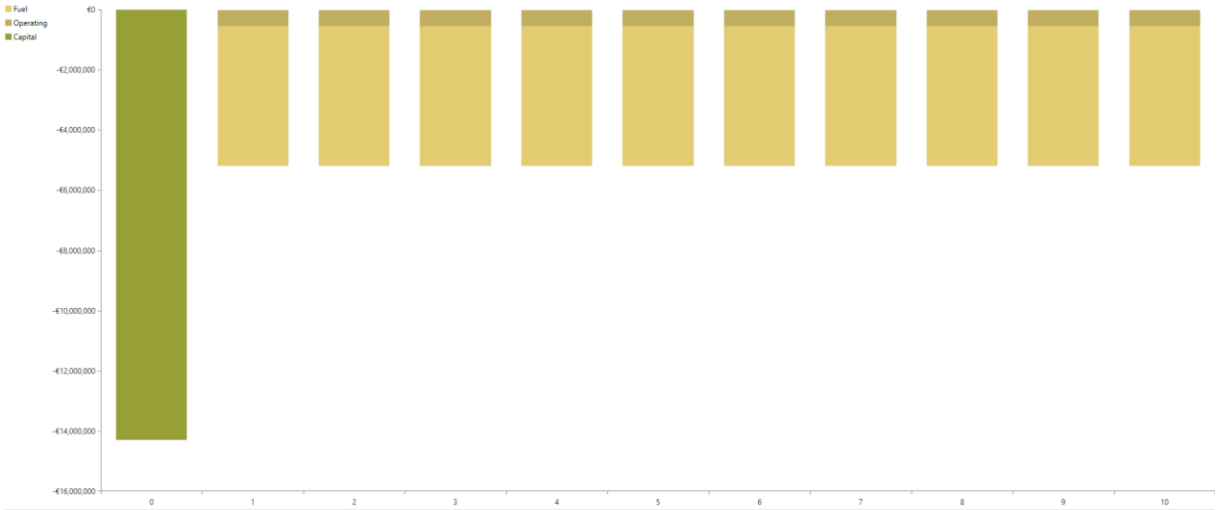


Figure 98 . Cash flow for Scenario 8.

4.10 Scenario 9

In scenario 9 , scenario 8 will be expanded with wind turbines,solar photovoltaics and energy storage. The Vestas V82 will be selected with a search space from zero to two. The Photovoltaic set up will remain the same as most scenarios at 3200 kW. For the battery bank n_{day}=4 will be selected like scenario 5 and scenario 6.

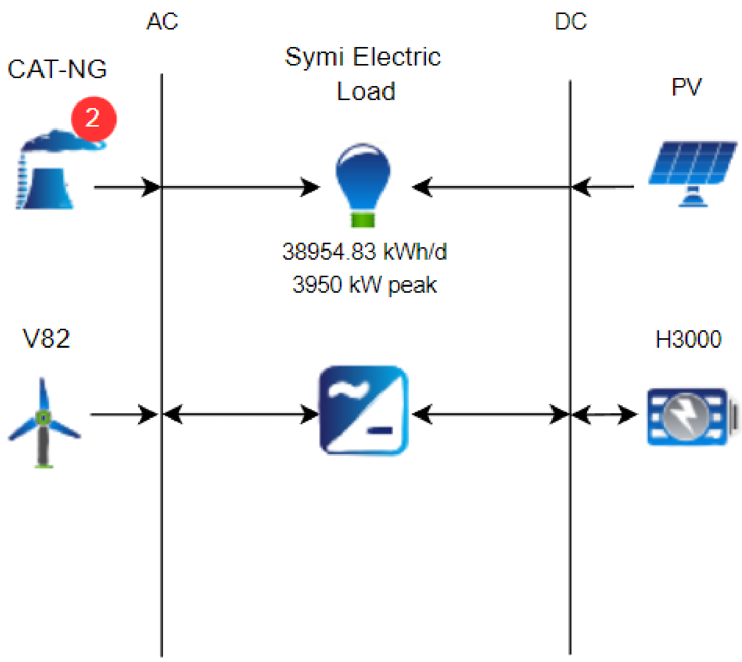


Figure 99 . Scenario 9 used for simulation in HOMER

The architecture result HOMER output are the shown in table #.

System	PV(kW)	Vestas V82	CAT-NG-2500kW-50Hz-CP G1	CAT-NG-2500kW-50Hz-CP G1	H3000	Converter (kW)	Excess Elec.(%)
Scenario 9	3,200	2	2000	2000	9,024	2,469	6.07

Table 74. HOMER PRO Optimised Architecture for scenario 9

More specifically each component is presented in the table below :

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption m^3/year	Operational Hours h/year
CAT-NG G1	2,259,889	14.0	1,424	947,600	2,335
CAT-NG G2	579,490	3.60	1,153	105,311	310
Vestas V82 [1.65MW]	7,581,815	47.1	866	-	7,313
Installed PVs	5,665,191	33.5	592	-	4,386
System	16,930,376	100			

Table 75. HOMER PRO component details for scenario 9

The load requirement the is met by mainly by wind turbines with 47.1% share in production followed by the installed PVs with 35.2% share. The system manages to achieve a renewable fraction of 80%. . Gas generators account for 17.6% of total output. Figure # shows the monthly electrical generation of each component. It is noticed that generator G2 only operates at the peak months of August.

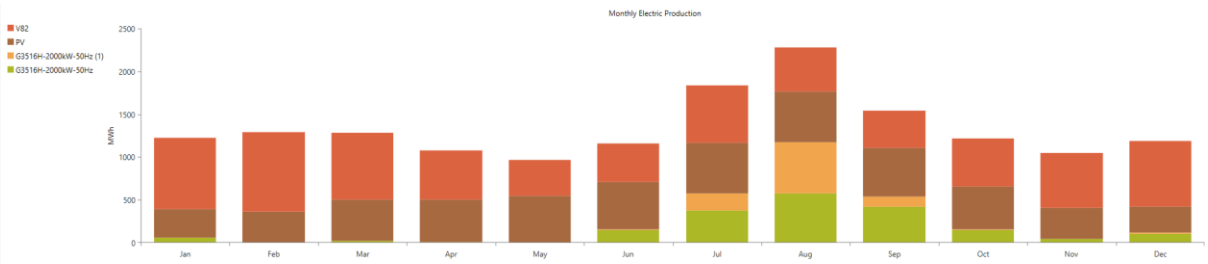


Figure 100. Monthly Electrical Production of Scenario 9.

From the above table it can be noticed that generator G1 was running all year round in order to satisfy load demand unmet by renewable energy sources or stored Energy except February. February is 100% renewably operated. Generator G2 is only needed when the system was at peak load during the month of Augst.

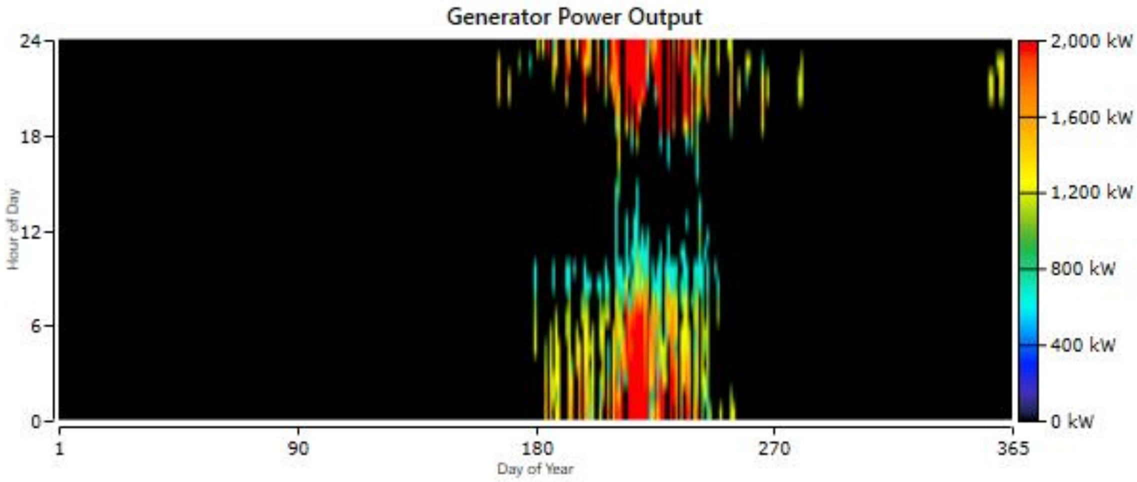


Figure 101. Yearly generator power output G1 for Scenario 1.

Quantity	Value	Units
Hours of Operation	683	hrs/yr
Number of Starts	98.0	starts/yr
Operational Life	11.7	yr
Capacity Factor	5.44	%
Fixed Generation Cost	172	€/hr
Marginal Generation Cost	0.295	€/kWh
Electrical Production	952,870	kWh/yr
Mean Electrical Output	1,395	kW
Minimum Electrical Output	700	kW
Maximum Electrical Output	2,000	kW
Fuel Consumption	233,764	m^3
Specific Fuel Consumption	0.245	m^3/kWh
Fuel Energy Input	2,308,420	kWh/yr
Mean Electrical Efficiency	41.3	%

Table 76. HOMER pro Yearly Values for generator G1 for Scenario 9.

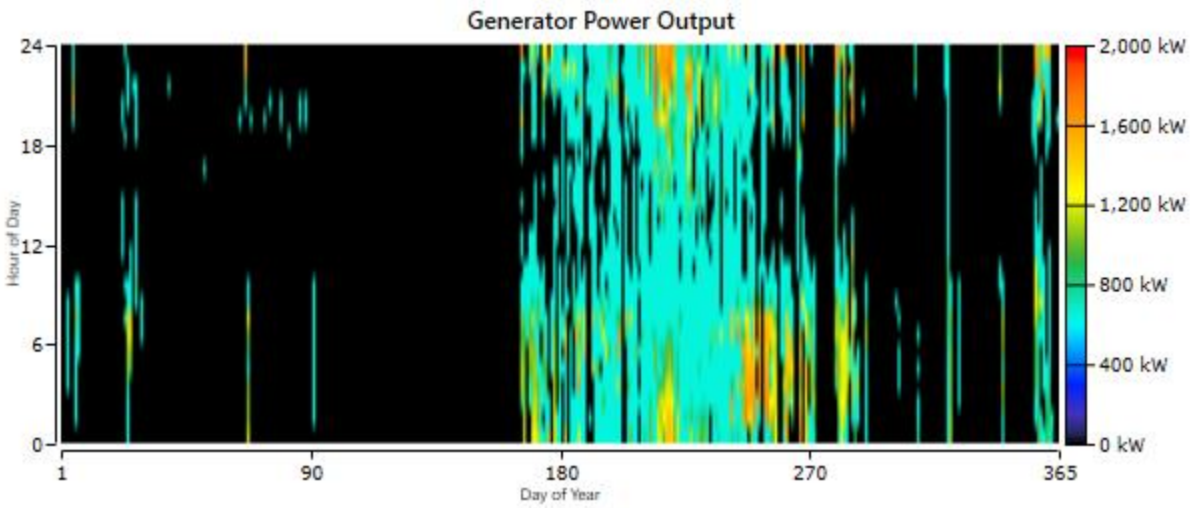


Figure 102. Yearly generator power output G2 for Scenario 9.

Quantity	Value	Units
Hours of Operation	2,267	hrs/yr
Number of Starts	190	starts/yr
Operational Life	9.48	yr
Capacity Factor	10.8	%
Fixed Generation Cost	93.7	€/hr
Marginal Generation Cost	0.295	€/kWh
Electrical Production	1,899,783	kWh/yr
Mean Electrical Output	838	kW
Minimum Electrical Output	700	kW
Maximum Electrical Output	1,942	kW
Fuel Consumption	498,053	m^3
Specific Fuel Consumption	0.262	m^3/kWh
Fuel Energy Input	4,918,273	kWh/yr
Mean Electrical Efficiency	38.6	%

Table 77. HOMER pro Yearly Values for generator G2 for Scenario 9.

The system yearly consumes 731,817 m^3/year of natural gas with an average of 2,005 m^3/day.

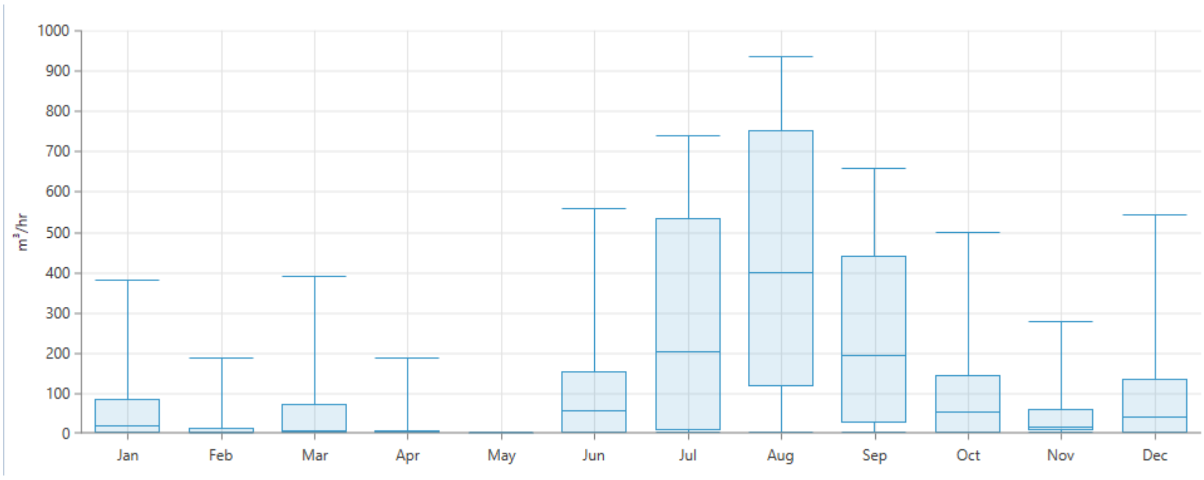


Figure 103 . Yearly fuel consumption for Scenario 9.

The Photovoltaics installation will remain at 3,200 kW . Figure # and Table # depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in June, July and August. The rated capacity of PV panels on this scenario is 3200 kW with a maximum power output of 2,805 kW.The total hours of operation of PV panels remains the same, which is to be expected at 4386 h/year.

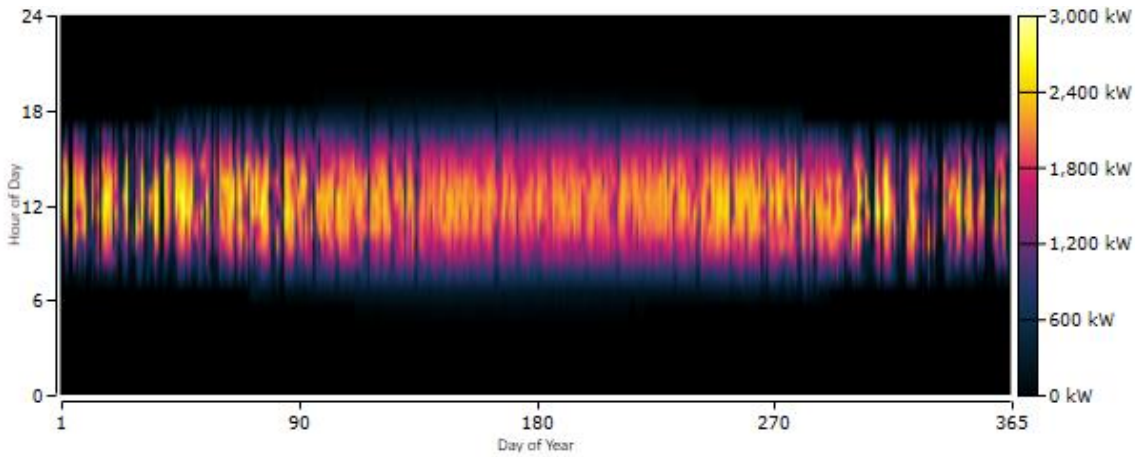


Figure 104. Hourly PV Power Production of Scenario 9.

Quantity	Value	Units
Rated Capacity	3,200	kW
Mean Output	648	kW
Mean Output	15,541	kWh/d
Capacity Factor	20.2	%
Total Production	5,672,538	kWh/yr
Minimum Output	0	kW
Maximum Output	3,295	kW
PV Penetration	39.9	%
Hours of Operation	4,386	hrs/yr
Levelized Cost	0.0992	€/kWh

Table 77. HOMER pro PV results for Scenario 9.

Figure 106 depict the hourly output power of Vestas V82, like scenario 5. Table 78 depicts the wind electricity production simulation results. Electricity generation is maximized during the winter season, with February having the largest average production .From the summer months, July has the largest energy production. The total rated capacity of the Vestas V82 in this scenario is 3,300 kW with a maximum power output of 3,390 kW.The total hours of operation of the wind turbines amount to 7,313 hrs/yr or 19 hours per day.

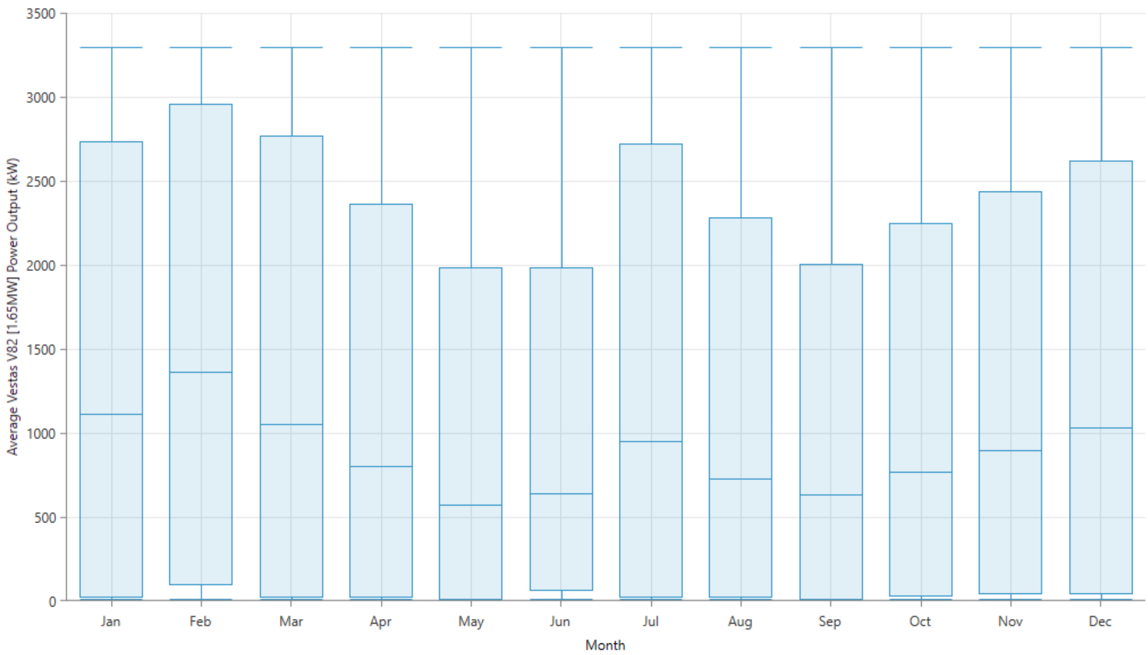


Figure 105. Monthly Power Output Average of Vestas V82 in scenario 7.

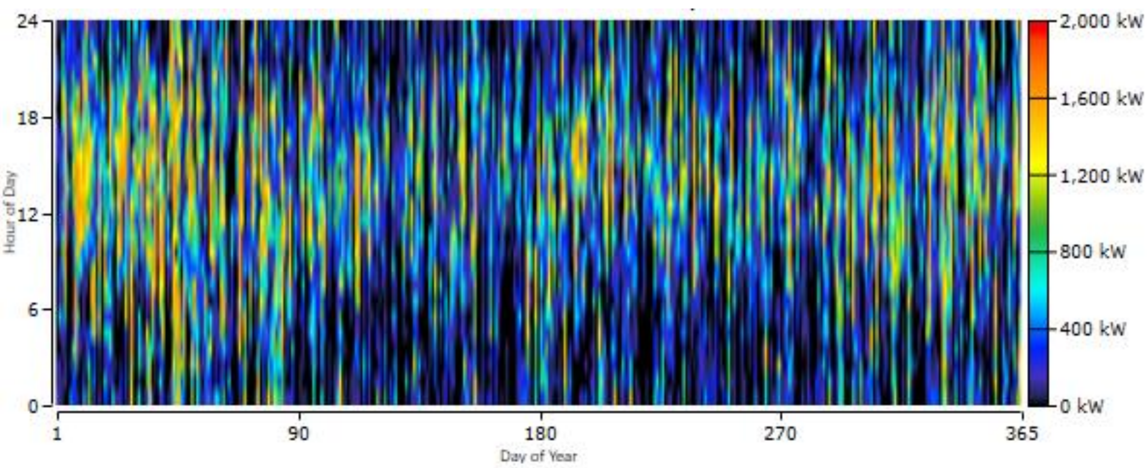


Figure 106. Hourly Wind Turbine Power output of Vestas V82 in Scenario 7.

Quantity	Value	Units
Total Rated Capacity	3,300	kW
Mean Output	866	kW
Capacity Factor	26.2	%
Total Production	7,581,815	kWh/yr
Minimum Output	0	kW
Maximum Output	3,341	kW
Wind Penetration	53.3	%
Hours of Operation	7,313	hrs/yr
Levelized Cost	0.107	€/kWh

Table 78. HOMER pro Vestas V82 results for Scenario 9.

In this scenario the storage bank is n_{day}=4 in order to make a comparison between scenario 4. Observing the state of charge frequency from Figure # below,that the batteries remain at a depth-of-charge of 30% with a frequency of 3.94% and at depth-of-charge of 100% with a frequency of 22.59%. The results of simulations of battery schemes are shown in Table 19. the results of which are presented in the table below:

Quantity	Value	Units
Batteries	9,024	qty.
String Size	12.0	batteries
Strings in Parallel	752	strings
Bus Voltage	24.0	V
Autonomy	27.8	hr
Storage Wear Cost	0.156	€/kWh
Nominal Capacity	64,515	kWh
Usable Nominal Capacity	45,161	kWh
Lifetime Throughput	38,012,487	kWh
Expected Life	10.0	yr
Average Energy Cost	0	€/kWh
Energy In	4,066,494	kWh/yr
Energy Out	3,525,133	kWh/yr
Storage Depletion	30,137	kWh/yr
Losses	571,498	kWh/yr
Annual Throughput	3,801,249	kWh/yr

Table 79. HOMER pro storage results for Scenario 9.

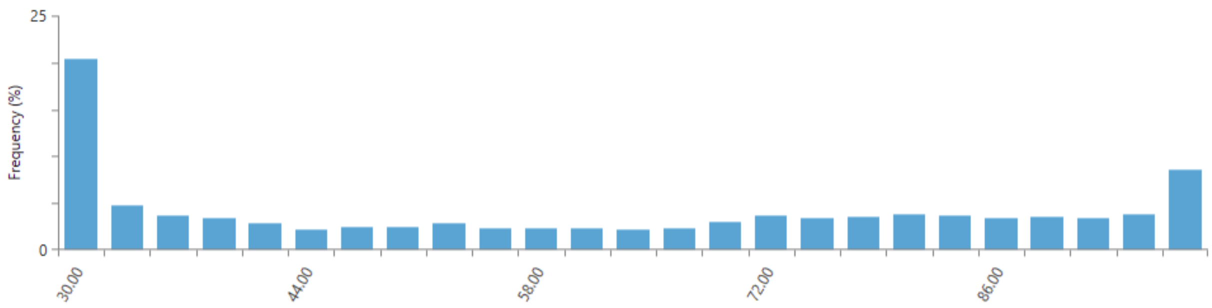


Figure 107. Hoppecke 24 OPzS 3000 state of charge frequency of Scenario 6.

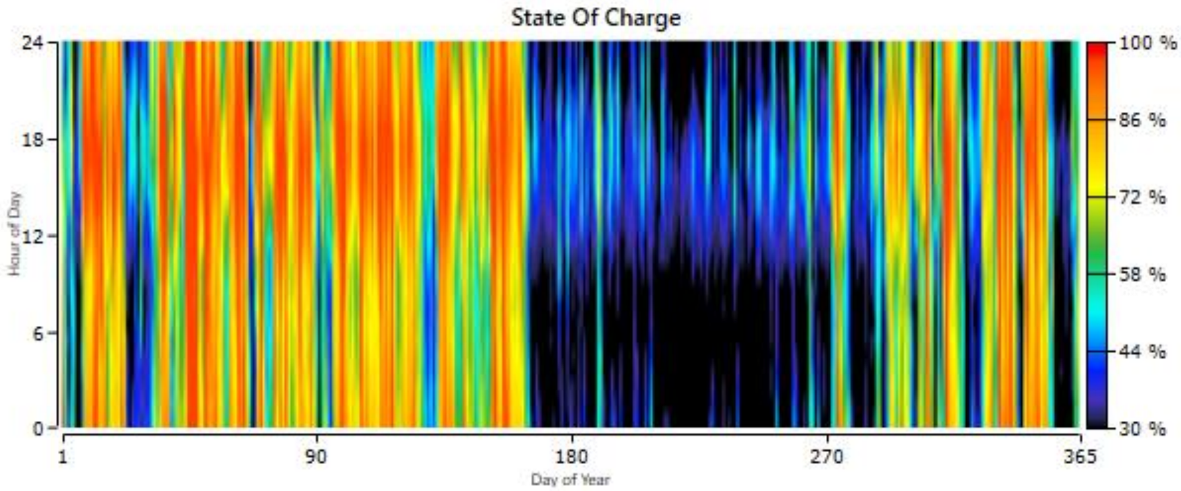


Figure 108. Hoppecke 24 OPzS 3000 state of charge of Scenario 9.

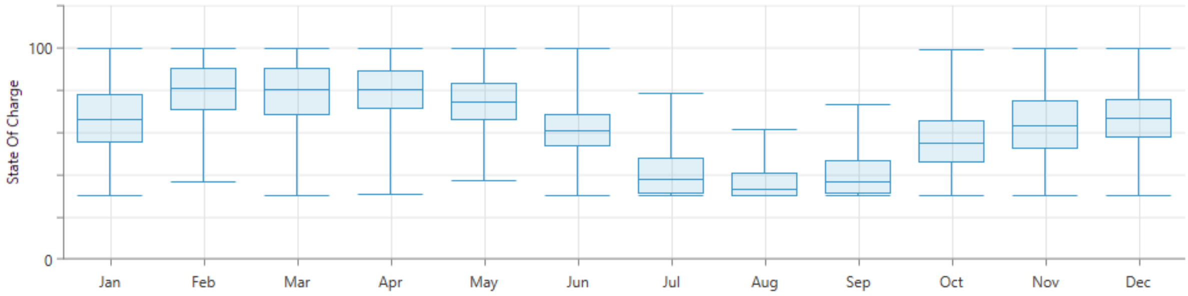


Figure 109. Hoppecke 24 OPzS 3000 monthly average state of charge of Scenario 9.

Excess electricity is observed during all months summer months. Most excess electricity is observed during February when wind power output is maxized, with an average excess electricity of 381.04 kW.

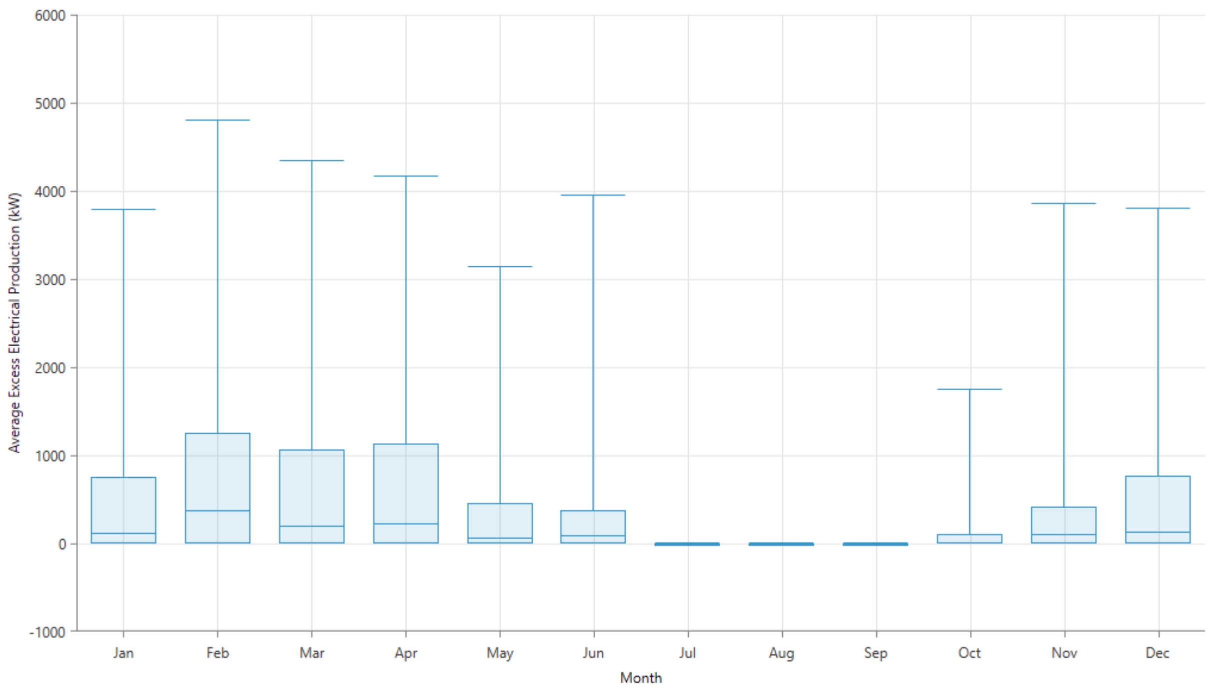


Figure 110. Monthly average excess electrical production of Scenario 9.

Economic Characteristic of Scenario 9:

The costs of fuel comes up at €980,634.81€/year compared to 1,343,476.224€/year for scenario 4 .

Total fuel consumed	**731,817**	**m³**
Avg fuel per day	2,005	m³/day
Avg fuel per hour	83.5	m³/hour

Table 80. Yearly fuel consumption Results of scenario 6

The economic aspects for the system are presented in Table 81.

Scenario	NPC(€)	COE(€)	Operating Cost(€)	Initial Capital(€)	Renewable Fraction	Total Fuel (m^3/yr)
Scenario 9	€63,688,370	€0.2972	€1,244,623	€44,933,019	80.0%	731,817

Table 81. HOMER PRO optimised results for scenario 9

Component	Capital(€)	Replacement(€)	O&M(€)	Fuel(€)	Total(€)
CAT-NG G1	€12,995,652	€0.00	€0.00	€4,720,302.89	€17,420,334.47
CAT-NG G2	€995,652.00	€1,948,798	€0.00	€10,056,982.11	€11,090,094.38
Hoppecke 24 OPzS 3000	€13,175,040.00	€0.00	€679,917.84	€0.00	€13,854,957.84
Installed PVs	€8,000,000.00	€0.00	€482,211.23	€0.00	€8,482,211.23
System Converter	€666,675.00	€0.00	€0.00	€0.00	€666,675.00
Vestas V82 [1.65MW]	€9,100,000.00	€0.00	€3,074,096.60	€0.00	€12,174,096.60
System	€44,933,019.00	€1,948,798	€4,236,225.67	€14,777,285.00	€63,688,369.52

Table 82. HOMER PRO sensetivity results for scenario 9

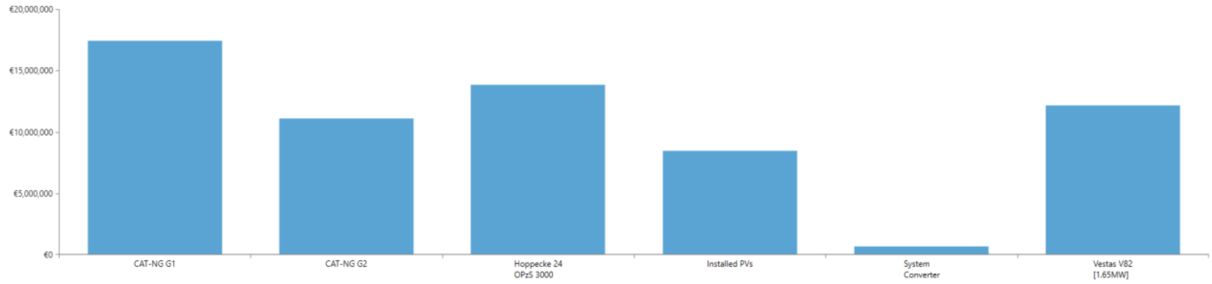


Figure 110. Net Present Cost Summary by component for Scenario 9.

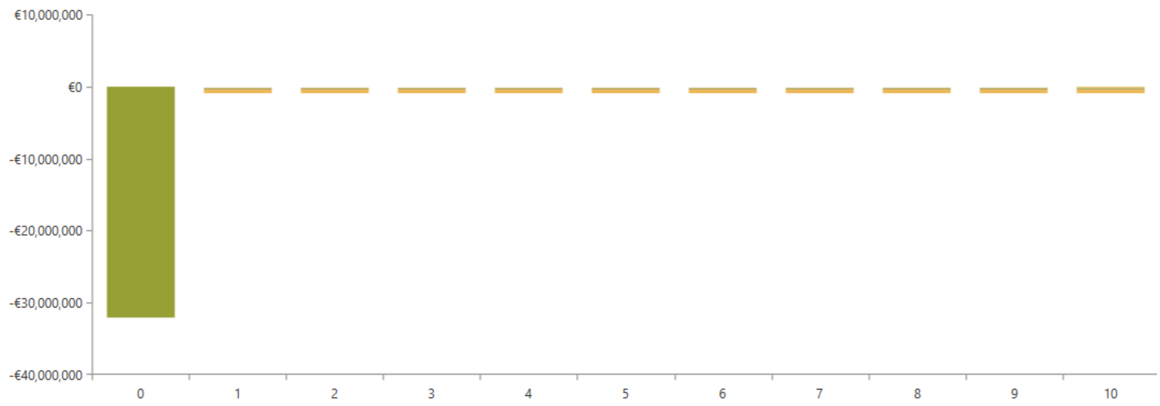


Figure 111. Cash flow for Scenario 9.

Chapter 5: Conclusion

Through this research, an effort was made to investigate the potential for using a hybrid renewable energy system for Symi Island that would rely more on available renewable energy technologies or alternative fossil fuels while being less reliant on fossil fuel power production. In order to do this, many techno-economic assessments with varied renewable fractions were carried out over a 10-year forecast period utilizing the HOMER program. On the basis of improved NPC and COE ideas, the best power production systems were chosen.

At the table below all systems are presented

Scenario	NPC(€)	COE(€)	Initial Capital(€)	Renewable Fraction	Excess Electricity
Base Scenario	92,657,260	0.4325	0	2.05%	0%
Scenario 1	€83,871,810	€0.3914	€5,072,600	26.9%	7.38%
Scenario 2	79,474,310	0.3709	€8,366,360	34%	0%
Scenario 3	€82,926,020	€0.3870	€12,900,696	34.2%	0%
Scenario 4	€54,466,330	€0.2542	€27,421,715.00	78.8%	5.08%
Scenario 5	€57,237,510	€0.2671	€27,961,075	77.3%	4.34%
Scenario 6	€55,983,807	€0.2613	€27,971,715.00	78.2%	4.65%
Scenario 7	€62,281,970	€0.2969	€52,693,197	100%	42.6%
Scenario 8	92,446,940€	0.4315€	14,294,34€	2.03%	0%
Scenario 9	€63,688,370	€0.2972	€44,933,019	80.0%	6.07%

Table 83. Total scenario results

From the above table, scenario 4 has the lowest NPC of €54,466,330 and COE of €0.2542 with 0.43% more excess electricity than the second rank scenario 6 and thus it is chosen as the most optimised scenario simulated. Even though scenario 4 is the most optimised system, with such a high renewable fraction, maintaining stable frequency should prove a technical challenge.

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