Escola Tècnica Superior
d'Enginyeria Química

FINAL MASTER PROJECT

MASTER IN ENVIRONMENTAL ENGINEERNG AND SUSTAINABLE ENERGY

Optimization of an Autonomous Microgrid linked with Energy Hydrogen Storage System

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Index

Contents

Nomenclature

RE	Renewable Energy
AC	Alternative current
COE	levelized cost of energy
DC	Direct current
DG	Distributed Generators
EHSS	Energy Hydrogen Storage System
FC	Fuel Cell
GWh	Gigawatt hour
kWh	kilowatt hour
LF	Load Following
MG	Microgrid
MWh	megawatt hour
NPC	total net present cost
REGs	Renewable energy generators
SPBP	Simple payback
TWh	Terawatt-hour

List Figures and Tables

Summary

This project analyses the optimal design of an autonomous microgrid, by discovering the ability of natural RE resources linked with EHSS to provide stable power. in order to present a complete approach of 100% RE sources, reduce pollution, and increase the electrical security supply in Tarragon city.

Natural renewable energy including wind (Onshore, Offshore), wave energy, and solar energy. they are participating in generating power to provide Tarragona load demand and the EHSS. EHSS was designed to cover as much as possible the energy shortages from REGs supplies

The work was developed based on the HOMER Pro software simulation model, by assuming three sizes of electrical load with real weather data, then the suitable size was selected. HOMER Pro proposes designs mainly based on economic performances for the system and the capacity shortage.

1. Introduction

Tarragona is a coastal city located in north-eastern Spain's Catalonia region, with a total area of 58 km², population:135,000 (Idescat. 2022). Between 2001 to 2006 there was increasing in population by 15.9%, and electric power consumption has also increased 42% (Documentació Agenda 21. 2006). The increasing in electric power demand in recent years has become a challenge for the existing power grids, due to the electricity high losses in transmission and increasing the operational cost. And most importantly, the electric power sector is responsible for about 1/3 of the global greenhouse gas emission (Hvelplund, F. 2006). Commitment to the Paris climate change agreement, Spain wants to reduce Carbon emission to 20% by 2030 and to net-zero carbon emission by 2050 (UNFCCC. 2015). To reach this ambitious goal, the Catalan government has established several targets. Increasing the Proportion of Renewable Energy (RE) from 8.7% in 2017 up to at least 27% in 2030 for all Energy consumed in Catalonia, and 50% Proportion of RE in the electricity sector (Villar et al., 2017).

Renewable energy generators (REGs) are totally dependent on nature, unlike fossil fuel generators. hence, it does not reliably ensure power quality and stable electric power. Therefore, its either required to be Grid-connected or connected to an energy storage system. Power transmission over long distances is inefficient and requires expensive infrastructure therefore, large amounts of clean energy and investments have been wasted recently, due to the power losses in and deficient capacity of power transmission lines (Pursiheimo et al., 2017).

Autonomous Microgrids offer a solution for integrated RE into the grid. the idea behind (MGs) is to shift from centralized power plants to Distributed Generators (DG), where the power will be generated nearby where it will be used, without the need to transmit it over long distances (Aldaouab, 2018). However, MGs with diesel Generators or Grid-connected to supply power demand in case of Insufficient RE, have an environmental impact, losses of energy, and high cost to the end-users (National Renewable Energy Laboratory (NR, 2012), (Best et al., 2007). Autonomous hybrid power generation systems or multi-agent systems are Promoted as an important alternative approach to be use for designing smart cities in the future. where autonomous MGs network, allows the surplus power to be shared between the MGs in the network. Each MG has its own REGs, energy storage systems, observer units, and intelligent electronic controller units.

A case study (Mohammed et al., 2014) in Brest, France. represent how a stand-alone hybrid system based on the solar power and EHSS, can supply the electric load demand of the town, also offer a cost-effective solution compared with the diesel generator based standalone power system.

Another case study (Haruni et al., 2013) focused on operation strategy for a standalone hybrid power system, where the operation strategy plays an important role to ensure the stability of the system. Power quality (Voltage deviation, Power factor deviation, and Total harmonic distortion) for a stand-alone hybrid power system can be improved by flexible AC transmission system (FACTS) devices, based on static VAR compensators, also offer a power efficiency compared with Grid-connected mode (Gabbar & Abdelsalam, 2014).

MGs cooperation provide power stability during sudden RE and load variations, and saves the total energy cost significantly, since energy surplus in one MG compensates the energy deficit in the other MG, before running the energy storage systems, to avoid the power losses during energy conversion process (Rahbar et al., 2018).

The load should be analysed in order to define MG size. however, there aren't enough studies about the optimal MG size. But there some studies mentioned the advantages of small-scaled MG. today the most available size in the market between 100 KW - 5 MW (Tazi et al., 2019).

2. Scope of The Project

The scope of the project is to design and determine the optimal REGs linked with a EHSS for an autonomous MG in Tarragona location. HOMER Pro software will be used to analyze and the design performance.

The project will study and evaluate only Load, REGs, EHSS, cost, and environmental impact. REGs include PV panels, Wind turbines (onshore & offshore), and wave turbine. EHSS includes Electrolyser, Hydrogen tank, and FC generator.

Nuclear, hydropower, tidal, and thermal energy are not included in MG design. Operation strategy and electrical connection method are out of the scope.

The contributions of the project are:

Discover the ability of natural RE resources linked with EHSS to provide a stable power in Tarragona location.

Explore the ability of EHSS to serve the load when there are not enough renewable resources.

Explore is there a chance the MGs replace the utility Grid under Tarragona city weather conditions.

Explore an approach to increase the electrical security supply from RE resources.

3. Method.

The methodology that following in this project to design a MG. Starting by analysing the electric load. defining and determining REGs and EHSS elements by HOMER Pro software.

HOMER Pro software (Hybrid Optimization of Multiple Energy Resources) is the global standard for optimizing microgrid design of energy resources. Has been developed by National Renewable Energy Laboratory (NREL) (HOMER Pro, 2022). Several hourly simulations are carried out for all MG elements to evaluate a linked REGs with EHSS in Tarragona city depending on several variables and conditions like cost, electrical load, solar irradiation, wind speed, and seawater speed.

REGs will start generating power to supply the electrical load. In the case of power surplus, the power will be converted into a Hydrogen gas by electrolyser. Hydrogen gas will be stored in a hydrogen tank, to be used in case of power deficiency from REGs, by converting the hydrogen gas to electricity through a FC generator as shown by Fig 3.1 The controller will control all of those operations based on information received through observer devices. the way how the controller works is known as operation strategy.

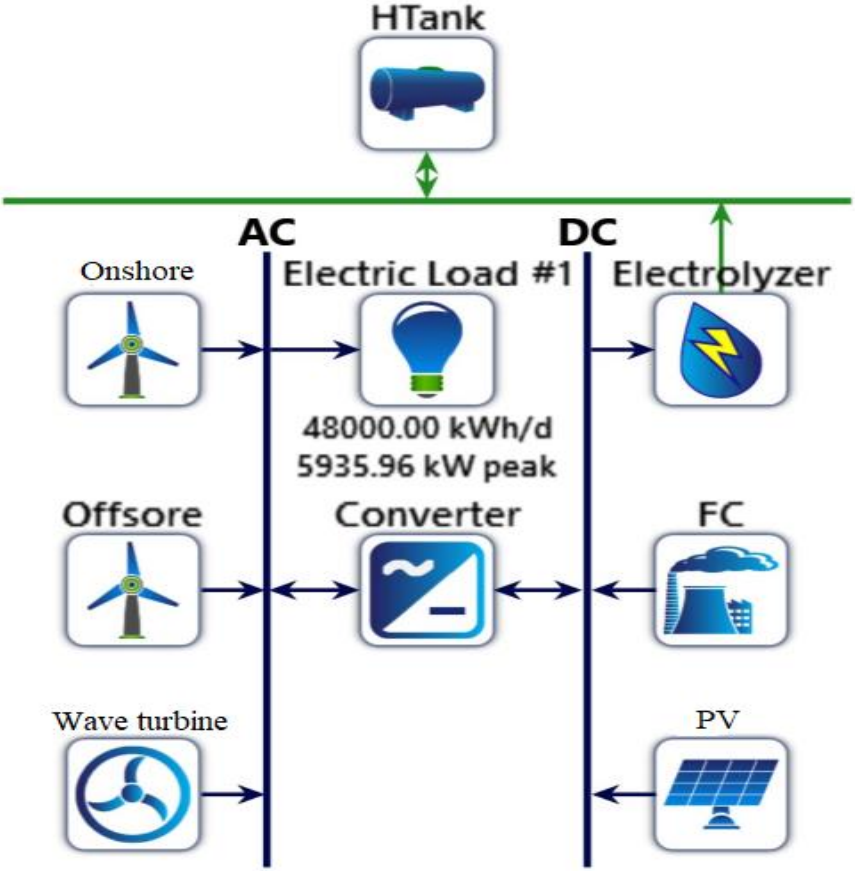


Figure 3.1 MG Structure

3.1. Load Profile Analysis.

Tarragona city has four loads type. The residential load represents 16.88%, commercial load 10%, municipal load 1.19% and industrial load 71.83% of the total load. The total load of the city has been scaled to 1.5 TWh/year. (Documentació Agenda 21. 2006). Each load type has a different annual and daily peak demand as shown in Table1. Currently the MG design based on a known small-scale load for like (university, school, residential compound.... etc). This project will deal with MG design for unknown large-scale load. Hence, the electric load type was chosen as a community load where include all electric sector in Tarragona city except industrial sector (Community Microgrids and Community Development, 2018). The daily and seasonal community load profile are shown in Fig A.1 and Fig A.2

Peak demand is one of the most parameters affecting the selection of the capacity of REGs and FC, where REGs and FC should supply the load with stable power during the peak period. however, increasing the capacity of REGs or FC to serve only the peak period, will lead to power excess in the off-peak times, also will increase NPC and COE. hence, three simulations will be carried out for three different size loads (1MW, 2MW, 3MW), to analyze which size load has the efficient capacity of REGs and FC.

Table 3.1 Load Specifications

	Residential load	Commercial load	Municipal	Industrial load
Annual load	251.3 GWh	150 GWh	17.77 GWh	1070 GWh
Daily peak hours	18:00 – 21:00	8:00 – 17:00	10:00 – 8:00	-
Annual peak period	Jul & Nov	Feb - Aug	Sep - Jun	Jan - Jun

3.2. Wind Turbines & Resource.

Wind turbines convert the kinetic energy of wind into electricity based on several conditions by the generator. A permanent magnet synchronous generator (PMSG) is used in this project to ensure coordination with the power regulation system, PMSG scheme shown in Fig A.3 The characteristics of the wind turbine that used in HOMER Pro software are shown in Table 3.2 & Fig A.4 Also, PMSG has several advantages, like low operational cost and maintenance, and high efficiency (Tani et al., 2015).

The energy generated by wind turbines can be expressed in equation 3.1

$$p = 0.5Cp\,(\lambda\,,\beta)\;A\;\rho\;v^3 \qquad (3.1)$$

Where p is output power, Cp is the power coefficient which is related to the speed ratio λ and the pitch angle β, A is the swept area, ρ which is the air density, and v is the wind velocity.

The wind speed data of Tarragona city were obtained from NASA Prediction of worldwide energy resources. Fig 3.3 HOMER Pro software will optimize the required number of turbines. Depicts the wind speed profile over a 30-year period.

The annual average wind speed for Tarragon city is 4.97 m/s.

Table 3.2 Wind Turbines Characteristics

	Onshore	Offshore
Name	Enercon E-115	Vestas V-164
Manufacture	Enercon	Vestas
Rated capacity	3000 KW	7000 KW
Cut-in speed	2.5 m/s	4 m/s
Cut-out speed	28 m/s	25 m/s

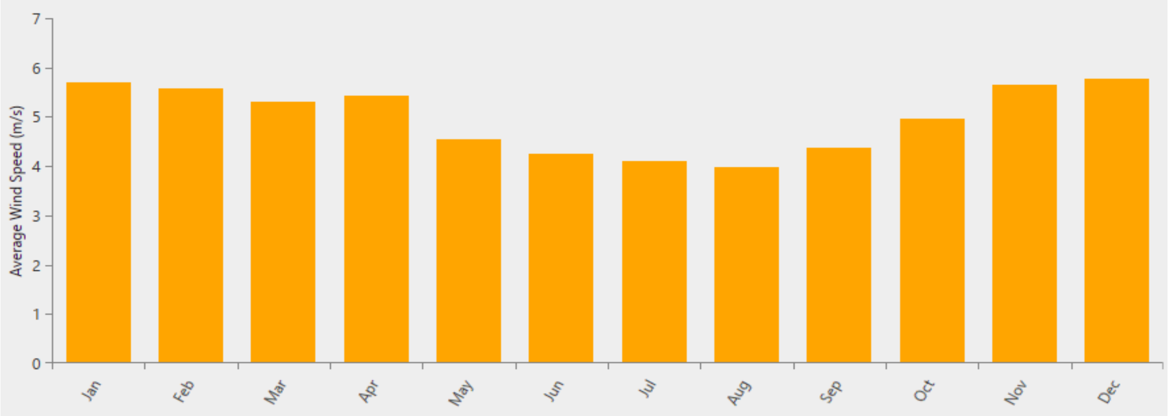


Figure 3.2 Wind Speed Profile

3.3. PV & Solar Resource.

PV array is a group of PV modules connected in series and parallel to match the required voltage and current. where the PV module consists of a fixed series and parallel PV cells combination (Al-Ammar et al., 2020) The power output from PV modules can be calculated in equation 3.2

$$p = \eta \, Ir \, A \tag{3.2}$$

Where p is the power output, η is the efficiency of PV module, Ir is the solar radiation, and A is the PV array area.

The characteristics of the PV panels that used in HOMER Pro software are shown in Table 3.3, Fig A.5& Fig A.6 HOMER Pro software will optimize the required capacity of PV.

Solar radiation data for Tarragona city were obtained from NASA Prediction of worldwide energy resources. Figure 3.4 depicts the solar radiation profile over a 22-year period. The annual average solar radiation for Tarragona is 4.34 kWh/m²/day.

Table 3.3 PV Module Characteristics

PV	Value
Name	Longi LR6-72HV-350M
Manufacturer	Longi Solar
Rated capacity	0.350 KW
Efficiency	18.1%
Type	Flat plate Mono-crystalline

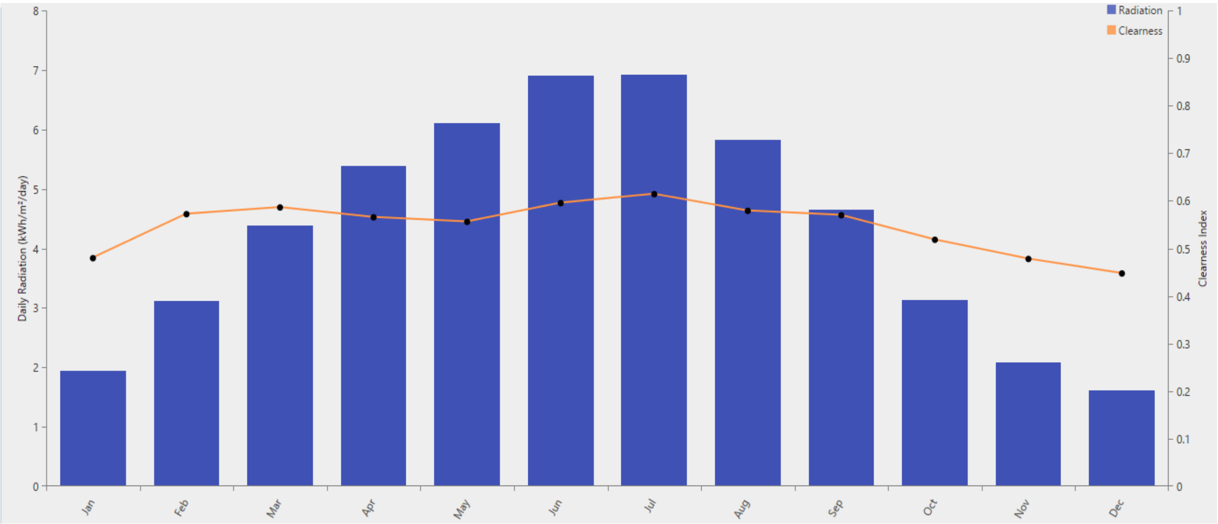


Figure 3.3 Solar Radiation Profile

3.4. Hydropower.

wave energy is relatively new compared with wind and solar energy, it has large market potential in several countries located next to the oceans, where the energy could be extracted from the wave movement on the ocean surface, however in this project we will analyze the wave energy on the coasts of the Mediterranean Sea (Falnes & Kurniawan, 2015).

The energy generated by wind turbines can be expressed in equation 3.3

$$p = \frac{\rho g A^2}{2} \tag{3.3}$$

Where p is the power output, ρ is the density of water, g the gravitational acceleration, and A is the amplitude of the wave.

Catalonia's seawater speed profile is shown in figure 3.5 where the annual average speed in the depth of 8 – 50 meters was 0.39 m/s (Marine Environment, 2021).

The characteristics of the wave Turbine that used in HOMER Pro software are shown in Table 3.4. HOMER Pro software will optimize the required number of turbines.

Table 3.4 Wave Turbine Characteristics

Turbine	Value
Name	Schottel [54KW]
Manufacturer	Schottel
Rated capacity	54 KW
Cut-in speed	0.7 m/s
Cut-out speed	4.6 m/s

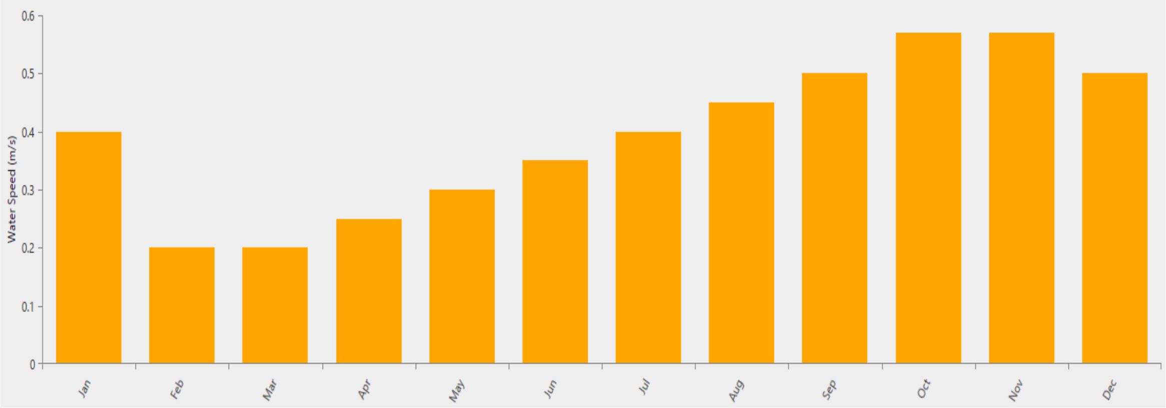


Figure 3.4 Seawater Speed Profile

3.5. Electrolyser.

Electrolyser converting the electricity into Hydrogen and Oxygen by anode and cathode. The reaction is shown in equation 3.4 & 3.5 More details in Fig A.6 & Fig A.7

Anode: $2H_2O \rightarrow 4H^+ + O2 + 4e$ (3.4)

Cathode: $4H^+ + 4e \rightarrow 2H_2$ (3.5)

The hydrogen production rate is shown in equation 3.6

$$MH_2 = \eta \frac{I_{el}}{2F} \qquad (3.6)$$

Where MH_2 is the hydrogen production rate, η the efficiency of the electrolyser, I_{el} is the working current, and F is the Faraday constant which equal to 96485C/mol (Zhang et al., 2020). HOMER Pro software will optimize the capacity required for the electrolyser.

3.6. Hydrogen Tank

Once the electrolyser is done from the hydrogen gas separation process, will be transferred to the storage tank. but to store sufficient amounts of hydrogen gas, high pressure would be needed or liquefy process due to the low density of hydrogen gas. Fig 3.6 (Dincer & Siddiqui, 2020) Shows the effect of pressure and temperature on hydrogen gas. liquefy process requires a low temperature, hence it would consider an expensive process. The hydrogen storage process is out of the project scope. HOMER Pro software will only calculate the required size of the hydrogen tank.

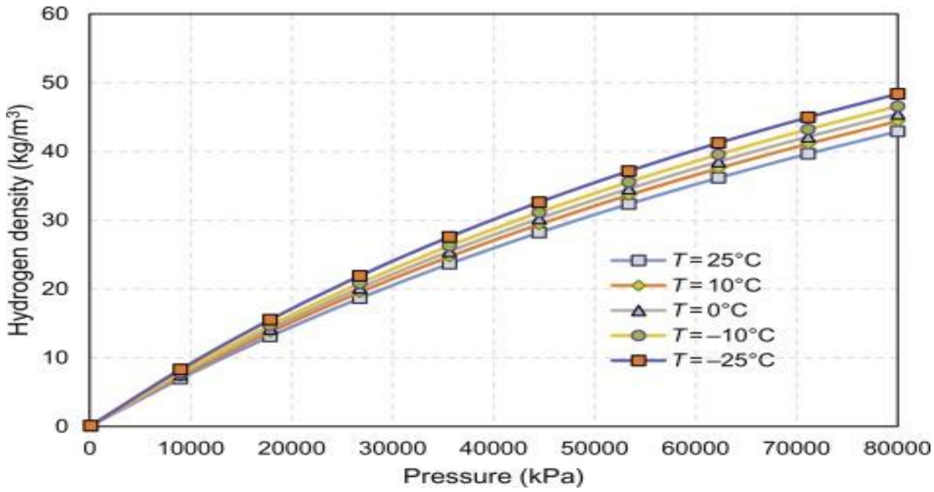


Figure 3.5 Hydrogen Density

3.7. Fuel Cell generator.

FC generator works to restore the hydrogen gas and oxygen into electricity (DC) and water. the reaction is shown in equations 3.7& 3.8 Catalysts are added to accelerate the electrode reaction in both anode and cathode (Zhang et al., 2020). More details in Fig A.8

Anode: $H_2 \rightarrow 2H^+ + 2e$ (3.7)

Cathode: $2H^+ + \frac{1}{2}O2 + 2e \rightarrow H_2O$ (3.8)

Hydrogen consumption can be calculated by formula 3.9. Hydrogen flow and FC efficiency are shown in Fig 3.7 & Fig 3.8. HOMER Pro software will optimize the size of FC. Where the selection was a generic FC.

$$mH_2use = 2mo_{2\,use} = \frac{\mathrm{I_{FC}}}{\mathrm{2F}} \quad (3.9)$$

Where mH_2use is the mass of hydrogen used, $mo_{2\,use}$ is the mass of oxygen used, I_{el} is the working current, and F is the Faraday constant which equal to 96485C/mol.

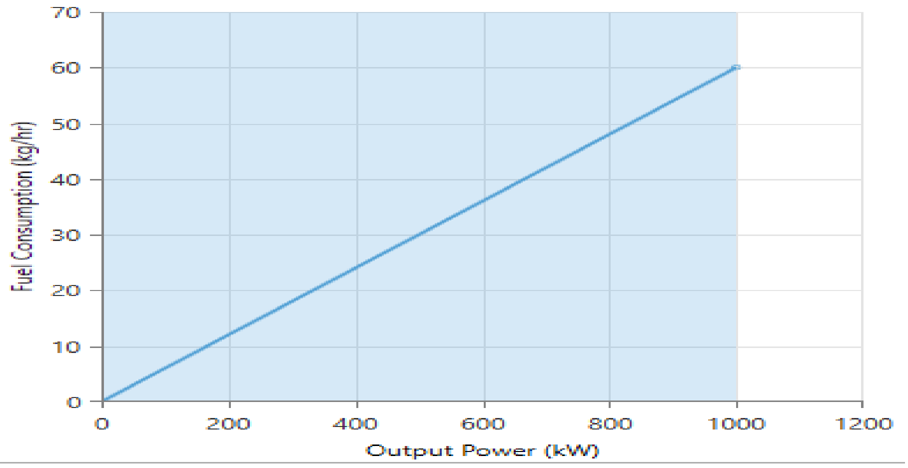


Figure 3.6 Hydrogen Flow

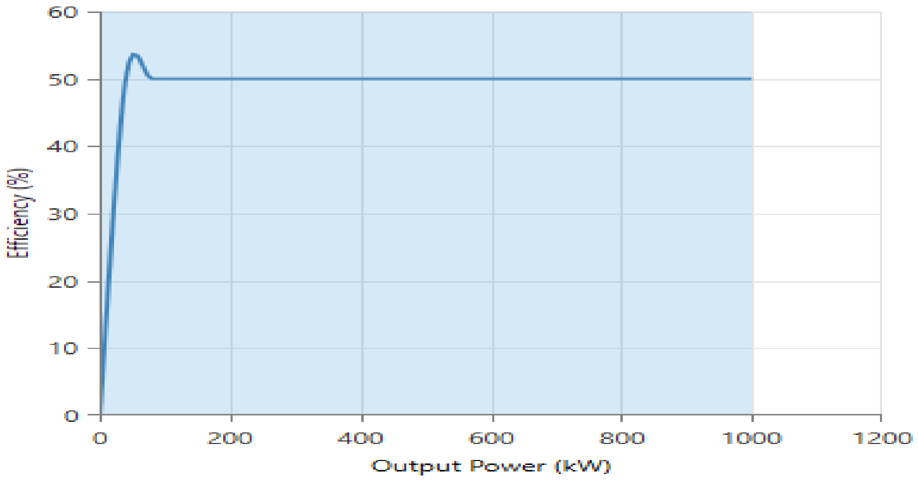


Figure 3.7 FC Efficiency

3.8. Converter.

In any combination of DC and AC components, an electrical rectifier/ inverter is needed. In this project, there are two loads, AC for the primary load, and DC for the electrolyser. PV modules and FC generate DC. Wind and wave turbines generate AC. as shown in Fig.3.1 Generic converters were selected in the simulations. HOMER Pro software will optimize the converter size and consider the power losses and cost. More details are shown in Fig A.9 & Fig A.10

3.9. Operation strategy.

The controller is coordinating between all the elements in the MG (Load, REGs, and ESS). In general, the priority of controller is to supply the primary load demand from REGs or ESS. Then in the case of surplus power, the controller sends a request to EHSS to start energy storage process (Zhang et al., 2020). Many issues start to appear when the system has several elements, such as different communication protocols, system memory, and system latency. (Esfahani et al., 2019), (Tazi et al., 2019). Recently researchers started to develop many operational strategies by Artificial Intelligence algorithms to improve the entire system performance.

HOMER Pro software offers several operational strategies. LF strategy was selected in this project due to its ability to deal with different REGs and ESS.

3.10. Economics

NPC show the economic status for the life cycle of the project. where can be calculated as shown in equation 3.10 (*Homer Pro*, 2022)

$$NPC = \sum_{t=0}^{N} \frac{ATC}{(1+ir)^{n}} + CC \tag{3.10}$$

Where ATC is the annual total cost, ir is the interest rate which is fixed in this project to be 8%, n is the year number, and CC is the capital cost. The lifetime of the project is fixed to be 25 years.

COE is the average cost per useful kWh generated from the system. COE can be calculated as shown in equation 3.11 (*Homer Pro*, 2022)

$$COE = \frac{AC}{E} \tag{3.11}$$

Where AC is the annual cost of the system, and E is the electrical load served.

SPBP is the required period to return the capital cost of the investment. SPBP can calculated as shown in equation 3.12 (*Net Present Cost (NPC)*, 2014)

$$SPBP = \frac{CC}{AS} \tag{3.12}$$

Where CC is the capital cost, and AS is the annual savings.

Table 3.5 show the economic input data in HOMER Pro software for all the system elements (Mohammed et al., 2014), (Longi.,2021), (McKenna et al., 2015), (*Homer Pro*, 2022)

Table 3.5 Economic Data.

Elements	Capital cost	Replacement cost	Maintenance Cost
Onshore turbine	2,000,000.00 $	2,000,000.00 $	42,000.00 $/ year
Offshore turbine	10,000,000.00 $	10,000,000.00 $	80,000.00 $/ year
Wave turbine	14,000.00 $	14,000.00 $	500.00 $/ year
Electrolyser	100.00 $/ kW	10.00 $	10.00 $/ year
Hydrogen tank	1,000.00 $/ 2,000 kg	100.00 $	10.00 $/ year
FC	3,000.00 $/ 5 kW	2,500.00 $	0.08 $/ op.hr
Converter	300.00 $/ kW	300.00 $	100.00 $/ year
PV	100.00 $/ kW	100.00 $	5.00 $/ year

4. Results and Discussion

Results were optioned from HOMER Pro software after several simulations for three different load sizes (1MW, 2MW, 3MW). for 1MW capacity it has a very high NPC $48.5M and COE 0.43$, also with 95% excess electricity as shown in Fig B.1 For 2MW capacity & 3MW capacity thy have the lowest COE 0.12$, as shown in Fig B.2 & Fig B.3 Where the differences in NPC $27M & $41M, and excess electricity 10% & 50%.

The load capacity was chosen in this project is 2 MW. Which means 48 MWh primary load per day. The peak demand for the primary load was scaled to 5.9 MW Fig 4.1

HOMER Pro software analysed the ability of the REGs to generate enough power under weather conditions and variable load during the year, to propose a design could match the primary load and electrolyser load. The environmental impact of the hybrid power system and economic data were analysed too.

4.1. Optimization Results

HOMER Pro was allowed to have an optimizer search space for wave and wind turbines (Onshore & Offshore) from zero - up to 5 turbines, PV from zero kW – up to 80 MW, electrolyser from zero kW – up to 5 MW, FC from zero kW – up to 5MW, and hydrogen tank size from zero kg – up to 30,000 kg.

The 2MW microgrid capacity requires 84.5 MWh/day and has a peak of 9 MW to serve the total load. Table 4.1 show the electrical consumption of the system loads. The primary load consumed 56.4 %, and the electrolyser consumed 43.6% of the total consumption. Fig 4.1 show the total load during the year.

In the best proposed system Fig B.4, the following generation sources in Fig 4.2 serve the total load. Were Onshore wind turbine generating 56.8 % of the total electrical production, PV 30.3 %, FC 12.9 %. Offshore wind turbine and wave turbine were not included in the best proposed system. Due to the high-cost compering with production, and slow water speed in The Mediterranean

Table 4.1 Electrical Consumption.

Load	Consumption (GWh/year)	Fraction
Primary	17.4	56.4%
Electrolyser	13.4	43.6%
Total	30.8	100%

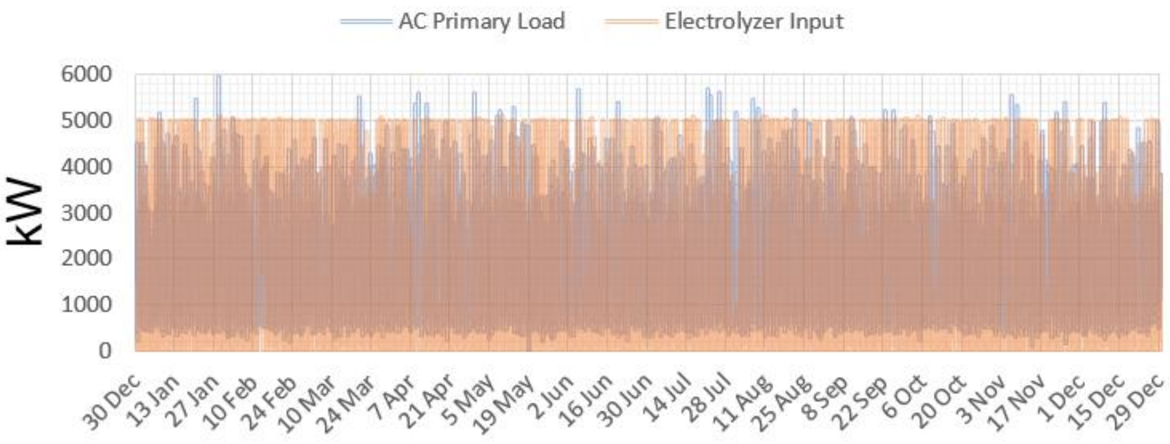


Figure 4.1 Load Profile

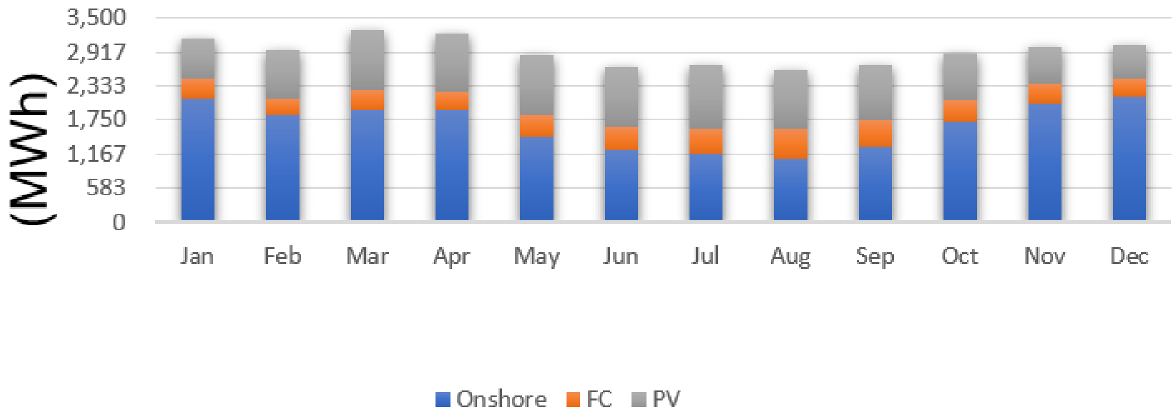


Figure 4.2 REGs Production

Two Onshore wind turbines were proposed for the hybrid power system with a total rated capacity of 6 MW and with a total production of 19.9 GWh/year in 8,626 operational hours. Fig 4.3 show the wind turbine power output during the year.

6.6 MW rated capacity of PV was proposed for the system with a total production of 10.6 GWh/ year in 4,369 operational hours. Fig 4.4 show the PV power output during the year.

Electrolysers capacity for the proposed system was 5 MW with 5,092 operation hours to produce 289,427 kg of hydrogen per year. Fig 4.5 show the electrolyser input power during the year.

FC production was 4.5 GWh/ year in 6,401 operation hours with total hydrogen fuel consumption of 270,349 kg. Fig 4.6 show the FC power output during the year.

The system requires a hydrogen tank with a size of 30,000 kg to have an energy storage capacity of 1 GWh. Fig 4.7 shows the tank level during the year.

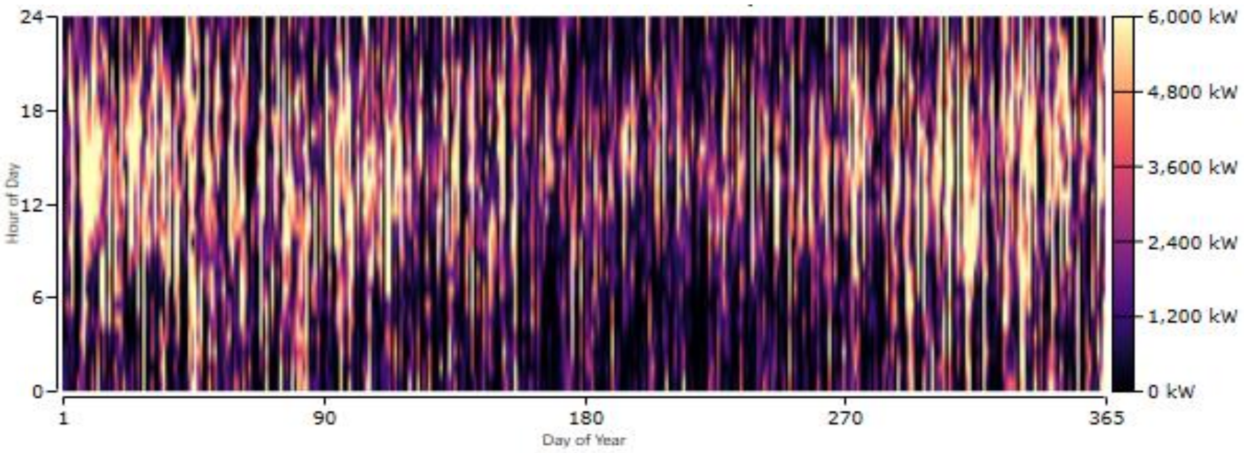


Figure 4.3 Wind Turbine Power Output

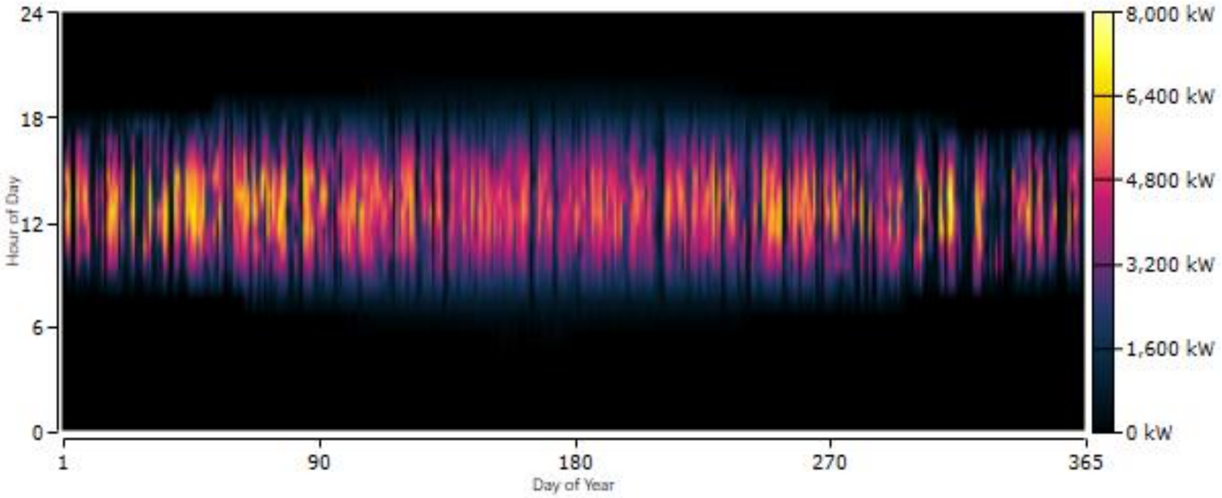


Figure 4.4 PV Power Output

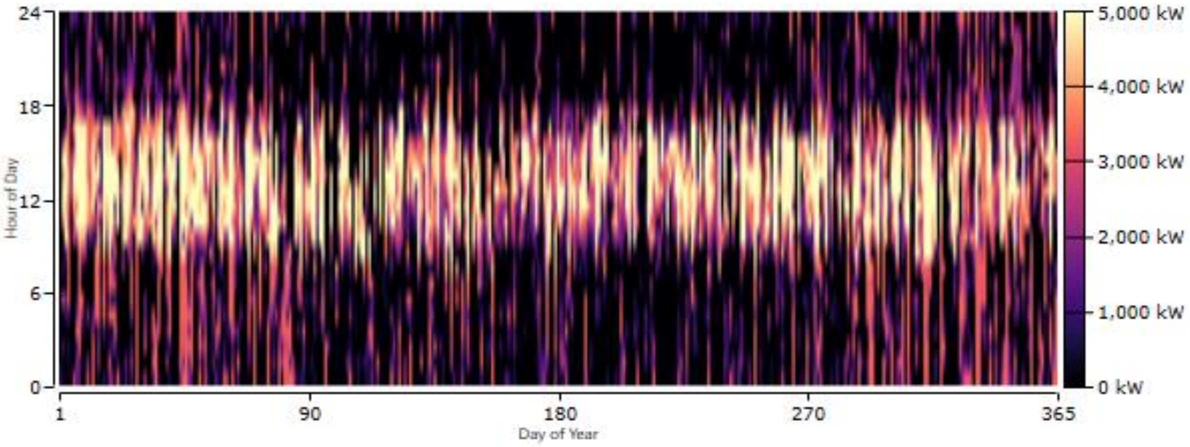


Figure 4.5 Electrolyser Input Power

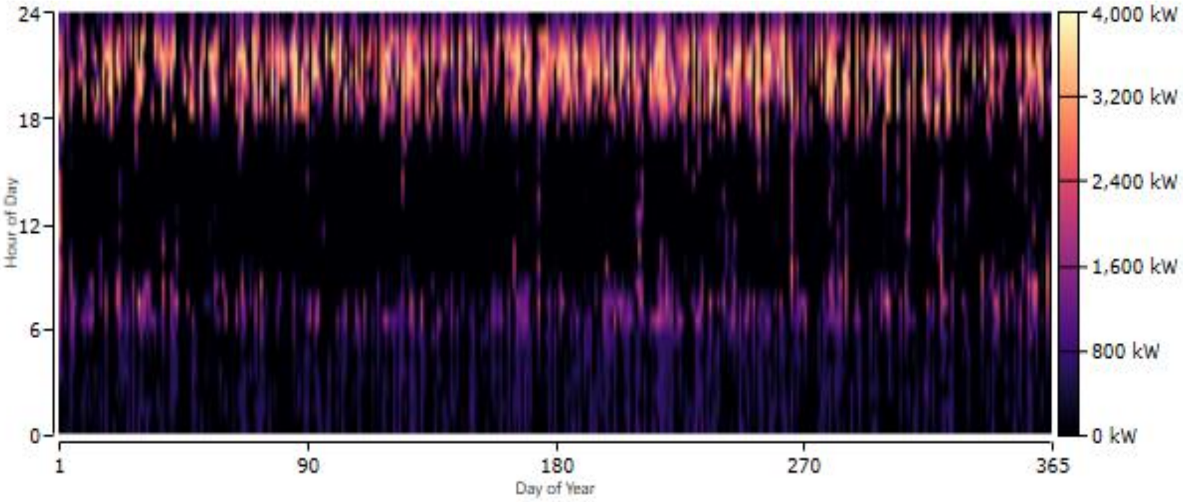


Figure 4.6 FC Power Output

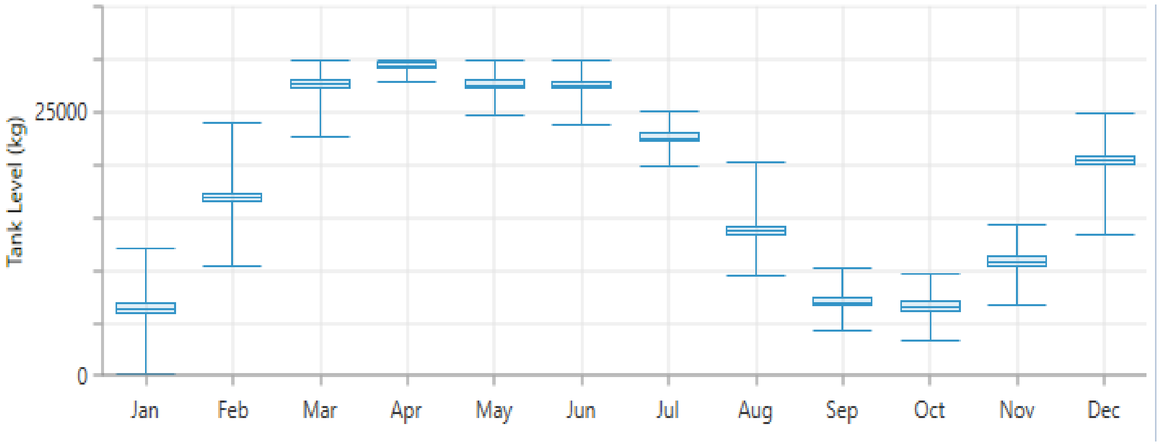


Figure 4.7 Hydrogen Tank Level

The system required a 3.3 MW Converters capacity (Inverter and Rectifier). The power losses in converters were 343.6 MWh out of 6.8 GWh. Table 4.2 Show the obtained converters data. Fig 4.8 & Fig 4.9 Show the inverter power output and rectifier power output during the year.

Table 4.2 Converters Data

	Inverter	Rectifier	Units
Capacity	3.3	3.3	MW
Energy In	6.8	6.2	GWh/ year
Energy Out	6.5	5.9	GWh/ year
Losses	343.6	313.7	MWh/ year

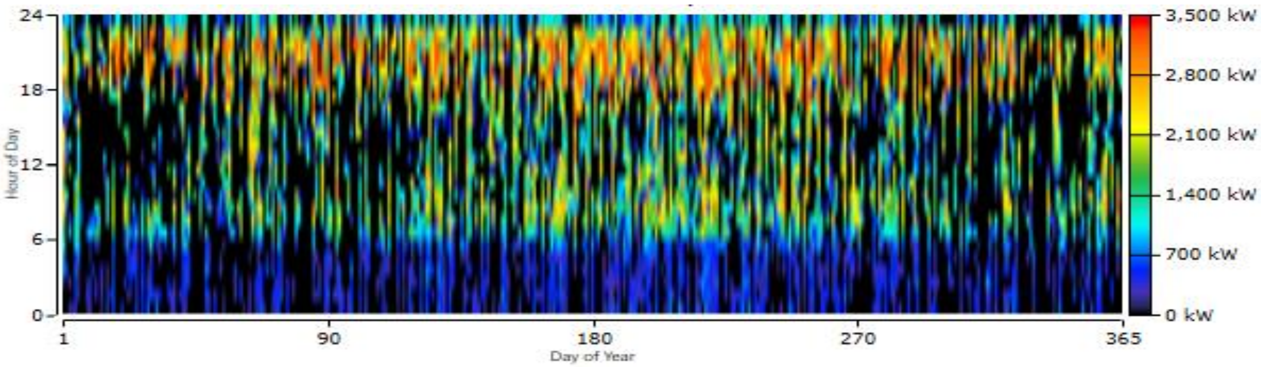


Figure 4.8 Inverter Output

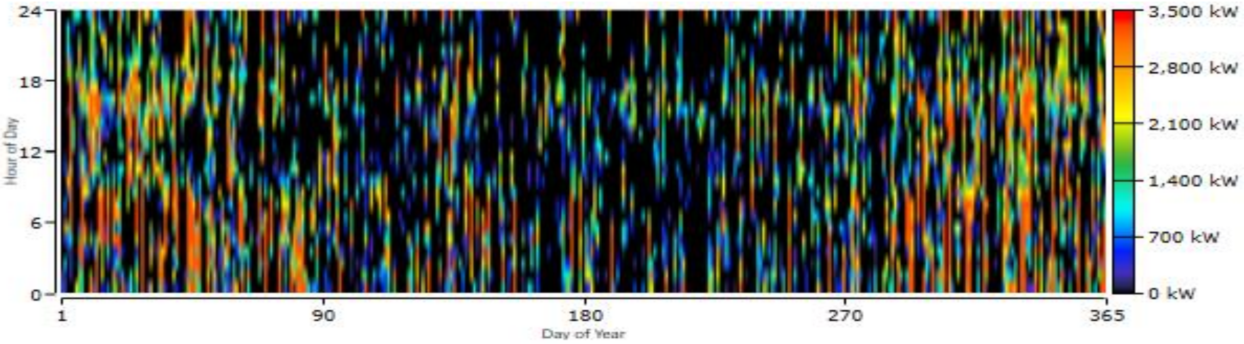


Figure 4.9 Rectifier Output

4.2. **Economical Results**

The system achieved a total NPC of $ 27.0M, where the initial capital cost is $9.18M and operating cost of $1.38M per year. Fig 4.10 show the cash flow over the project lifetime and table 4.3 show the cash flow by component.

COE for the project is 0.120 $/kWh, which means 51.2% less than the current electric tariff in Catalonia.

The project has SPBP almost within 14 years, its long period for commercial project, but it’s not for environment project.

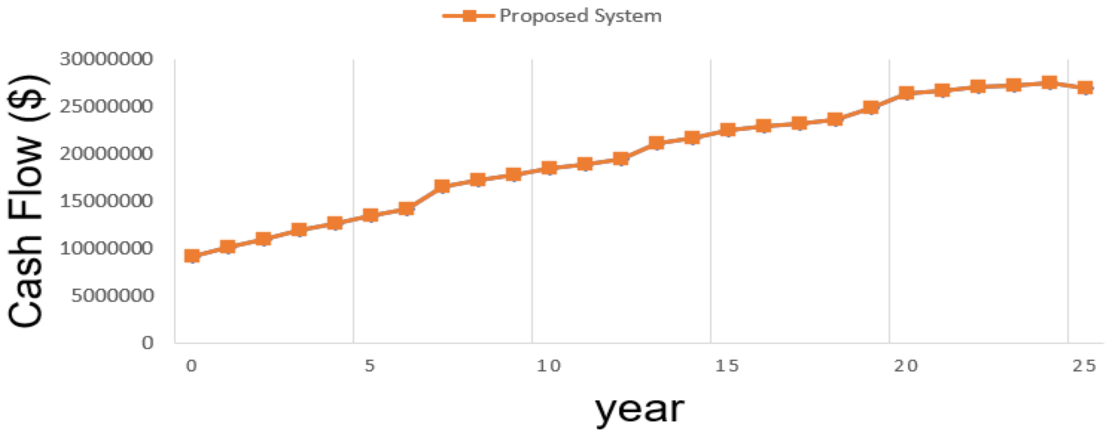


Figure 4.10 Cash Flow

Table 4.3 NPC

Component	Capital ($)	Replacement ($)	O&M ($)	Salvage ($)	Total ($)
Onshore	4.00M	1.2M	1.08M	0.71M	5.64M
FC	3.00M	3.8M	6.61M	0	13.44M
Electrolyser	0.5M	0.015M	0.64M	0.009M	1.15M
Hydrogen Tank	0.015M	0	0.0019M	0	0.016M
Solar PV	0.66M	0	0.43M	0	1.09M
System Converter	1M	0.4M	4.31M	0.07M	5.66M
System	9.18M	5.5M	13.10M	0.80M	27.02M

4.3. Environmental Impacts

As the result of burning fossil fuels to generate electricity, the main environmental impact is the production of CO2 and SO2, where two are responsible for global warming, environmental pollution, and human diseases.

Also, there are several substances that are produced during the electricity generation process such as CO, PM, NOx, and UHCs. however, they have less impact than CO2 & SO2 (U.S. Energy Information Administration, 2021).

Regarding the REGs life cycle emission, REGs are not totally zero emission due to the manufacturing process, where Solar PV has the highest environmental impact and Onshore wind turbines have the less impact (WNA, 2021). Table 4.4 show the annual emission of the project.

Table 4.4 Annual Emission

Pollutant	Symbol	Value	Units
Carbon Dioxide	CO2	-2,761	Kg/year
Carbon Monoxide	CO	1,757	Kg/year
Nitrogen Oxides	NOx	15,680	Kg/year
Particulate Matter	PM	132	Kg/year
Sulphur Dioxide	SO2	0	Kg/year
Unburned Hydrocarbons	UHCs	195	Kg/year

4.4. MG Architecture

The 2 MW MG capacity will provide electricity to almost 4,940 houses. where the average house consumption is 3.5MWh/ year. several sites should be chosen to install REGs and EHSS.

the MG requires two onshore wind turbines, 19,052 PV panels, and a power plant for EHSS where the electrolyser, tanks, and FC are located near each other, without the need for hydrogen transportation or hydrogen infrastructure.

Wind turbines can be installed in the north cityside, to give more wind potential. also, city dwellers will avoid turbines noises. the power plant can also be installed in the northeast of the city near to the sea. where it will be close enough to the city and wind turbines. PV panels either can be installed in a PV solar farm or in several locations like building's rooftops, car parking. Converters will take a place in several location as shown in Fig 4.11

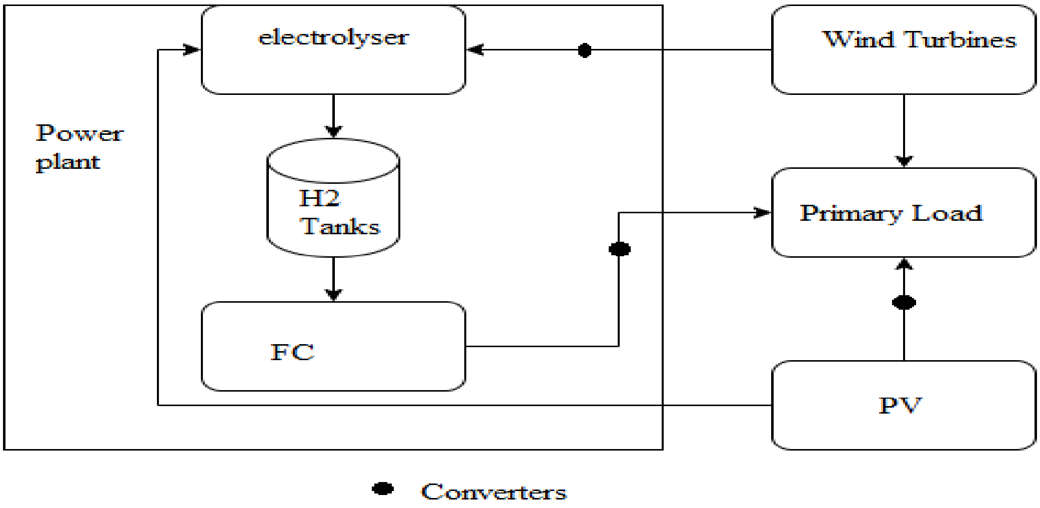


Figure 4.11 MG Architecture

4.5. Drawbacks and Recommendations

One of the most common drawbacks for any autonomous MG linked only with REGs is the capacity shortage, where there are not enough renewable recourses for generating enough power to meet the load demand. which will lead to blackouts for the users. this MG has 123.5 MWh/year unmet load. Fig 4.12 & Fig B.5 show the unmet load and electrical data during the year. The longest duration of blackouts was for a hour, which can be served by supercapacitor or lithium batteries.

There is a 10.1% electricity excess Fig B.5, the excess can be sold or charged to the batteries in case of existing.

FC required time to convert hydrogen to electricity. in case of sudden high demand, the FC cannot serve the load directly. which will cause blackouts. unlike supercapacitors and batteries, they can directly provide electricity. however, the required time for FC to start to serve the demand is not long, supercapacitors will ensure power stability.

Transformers may be required for the high voltage out from wind turbines, whereas HOMER Pro doesn't include this type of calculation.

The economic results are not 100% accurate, where installation costs and salaries were not included.

The unmet load could be decreasing during the next years, where HOMER Pro software calculates the energy production for only the first year. the hydrogen tank was almost empty at the being of the first year and full at the end of the year, which REGs and FC could supply more load in the first months in the second year without the need for Hydrogen production. However, external REGs could be installed to supply only the EHSS, with upgrading the hydrogen tank and FC capacity.

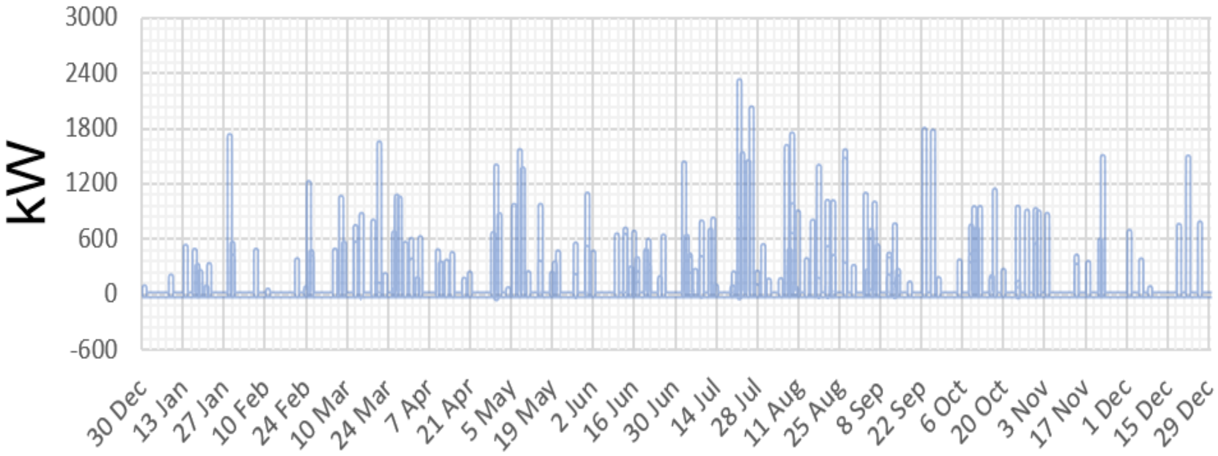


Figure 4.12 Unmet Load

5. Conclusion.

The project shows how the peak demand significantly affects the mix of REGs and EHSS, where 2MW capacity has the lowest COE and power losses. Then the project has developed an autonomous MG design with 2MW capacity by using REGs and EHSS, considering the available potential for all-natural RE resources in Tarragona city. To supply 4,940 houses with electricity.

The onshore wind turbine has more ability to generate electricity at a lower price compared with Offshore wind turbines, due to the high cost of the offshore wind turbine and low wind speed. The Mediterranean Sea has a very slow wave speed hence, wave energy was excluded. Onshore wind turbines and Solar PV were the key players in energy-generating as shown in table 5.1

Large scale MG linked with EHSS has a high chance to replace the utility Grid for an urban city in the future, by creating MGs network, since the EHSS has a very high ability to supply and ensure the power stability, where the unmet load didn't reach up 0.75% of the total load, with expecting less unmet load in the next years, due to the high hydrogen production in the first year. Also, there is 10% excess power, the excess power can be sold or charged to the batteries in case of existing.

The MG linked with EHSS would provide electricity to the users with less and fixed price during the lifetime of the project compared to the utility grid, where the electricity price is linked to fossil fuel and gas prices. RE technologies, Electrolysers, and FC will have higher efficiency and less cost as expected in the future, hence the COE will drop down too.

The MGs will be a promising solution in the future to achieve the government’s ambitious goal, having zero carbon emissions from electricity generation and reducing losses in electricity transmission.

Table 5.1 MG Elements

MG Elements	Consumption		Production	
		Unit		Unit
Onshore	No consumption	-	19.9	GWh/year
Offshore	Not exist	-	Not exist	-
Wave Turbines	Not exist	-	Not exist	-
Solar PV	No consumption	-	10.6	GWh/year
Electrolyser	13.4	GWh/year	289,427	Kg/year
FC	270,349	Kg/year	4.5	GWh/year
Converter	6.8	GWh/year	5.9	GWh/year
Primary Load	17.4	GWh/year	-	GWh/year

6. **References.**

Al-Ammar, E. A., Habib, H. U. R., Kotb, K. M., Wang, S., Ko, W., Elmorshedy, M. F., & Waqar, A. (2020). Residential Community Load Management Based on Optimal Design of Standalone HRES With Model Predictive Control. *IEEE Access*, *8*, 12542–12572. https://doi.org/10.1109/access.2020.2965250

Aldaouab, I. (2018, November 5). *Renewable Energy Microgrid Design for Shared Loads*. IntechOpen. https://www.intechopen.com/chapters/60785

Best, R. J., Morrow, D. J., McGowan, D. J., & Crossley, P. A. (2007). Synchronous Islanded Operation of a Diesel Generator. *IEEE Transactions on Power Systems*, *22*(4), 2170–2176. https://doi.org/10.1109/tpwrs.2007.907449

Community microgrids and community development. (2018). Advisian. https://www.advisian.com/en/global-perspectives/community-microgrids---offering-grid-modernization-and-community-development#

Dincer, I., & Siddiqui, O. (2020). Types of fuels. *Ammonia Fuel Cells*, 33–76. https://doi.org/10.1016/b978-0-12-822825-8.00003-7

Documentació Agenda 21. (2006). tarragona. https://www.tarragona.cat/neteja-i-medi-ambient/fitxers/fitxers-antic-mediambient/altres/documentacio-agenda21

EE&RE. (2015). *FUEL CELL TECHNOLOGIES*. https://www.energy.gov/sites/prod/files/2015/11/f27/fcto_fuel_cells_fact_sheet.pdf

Esfahani, M. M., Hariri, A., & Mohammed, O. A. (2019). A Multiagent-Based Game-Theoretic and Optimization Approach for Market Operation of Multimicrogrid Systems. *IEEE Transactions on Industrial Informatics*, *15*(1), 280–292. https://doi.org/10.1109/tii.2018.2808183

Falnes, J., & Kurniawan, A. (2015). *Fundamental formulae for wave-energy conversion*. Royal Society Publishing. https://royalsocietypublishing.org/doi/10.1098/rsos.140305

Gabbar, H. A., & Abdelsalam, A. A. (2014). Microgrid energy management in grid-connected and islanding modes based on SVC. *Energy Conversion and Management*, *86*, 964–972. https://doi.org/10.1016/j.enconman.2014.06.070

Haruni, A. M. O., Negnevitsky, M., Haque, M. E., & Gargoom, A. (2013). A Novel Operation and Control Strategy for a Standalone Hybrid Renewable Power System. *IEEE Transactions on Sustainable Energy*, *4*(2), 402–413. https://doi.org/10.1109/tste.2012.2225455

Homer Pro. (2022). Https://Www.Homerenergy.Com. https://www.homerenergy.com/products/pro/docs/3.14/index.html

HVELPLUND, F. (2006). Renewable energy and the need for local energy markets. *Energy*, *31*(13), 2293–2302. https://doi.org/10.1016/j.energy.2006.01.016

Idescat. The municipality in figures. (2022, January 15). Gencat. https://www.idescat.cat/emex/?id=431482&lang=en

IRNA. (2020). *GREEN HYDROGEN*. https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf

marine environment. (2021). Port de Barcelona. https://www.portdebarcelona.cat/es/web/el-port/oceanografia-fisica/#:~:text=En%20la%20capa%20de%20agua,0%2C20%20m%2Fs

McKenna, R., Hollnaicher, S., Ostman V. D. Leye, P., & Fichtner, W. (2015). Cost-potentials for large onshore wind turbines in Europe. *Energy*, *83*, 217–229. https://doi.org/10.1016/j.energy.2015.02.016

Mohammed, O. M. A. R., Amirat, Y., Benbouzid, M., & Elbast, A. (2014). Optimal Design of a PV / Fuel Cell Hybrid Power System for the City of Brest in France. *HAL*.

National Renewable Energy Laboratory (NR. (2012). *Role of Energy Storage with Renewable Electricity Generation*. BiblioGov.

Net Present Cost (NPC). (2014). Ebrary. https://ebrary.net/32824/environment/cost#827

NXP. (2011). *Inverter for the solar panel*. https://www.nxp.com/docs/en/reference-manual/DRM126.pdf

Pursiheimo, E., Holttinen, H., & Koljonen, T. (2017). Path toward 100% renewable energy future and feasibility of power-to-gas technology in Nordic countries. *IET Renewable Power Generation*, *11*(13), 1695–1706. https://doi.org/10.1049/iet-rpg.2017.0021

Rahbar, K., Chai, C. C., & Zhang, R. (2018). Energy Cooperation Optimization in Microgrids With Renewable Energy Integration. *IEEE Transactions on Smart Grid*, *9*(2), 1482–1493. https://doi.org/10.1109/tsg.2016.2600863

Shen, J., & Khaligh, A. (2015). A Supervisory Energy Management Control Strategy in a Battery/Ultracapacitor Hybrid Energy Storage System. *IEEE Transactions on Transportation Electrification*, *1*(3), 223–231. https://doi.org/10.1109/tte.2015.2464690

Tani, A., Camara, M. B., & Dakyo, B. (2015). Energy Management in the Decentralized Generation Systems Based on Renewable Energy—Ultracapacitors and Battery to Compensate the Wind/Load Power Fluctuations. *IEEE Transactions on Industry Applications*, *51*(2), 1817–1827. https://doi.org/10.1109/tia.2014.2354737

Tazi, K., Abbou, F. M., & Abdi, F. (2019). Multi-agent system for microgrids: design, optimization and performance. *Artificial Intelligence Review*, *53*(2), 1233–1292. https://doi.org/10.1007/s10462-019-09695-7

United Nations Framework Convention on Climate Change (UNFCCC). (2015). https://unfccc.int/resource/docs/2015/cop21/eng/l09.pdf

U.S. Energy Information Administration. (2021, December). *Electricity and the environment*. Energy Information Administration. https://www.eia.gov/energyexplained/electricity/electricity-and-the-environment.php

Villar, D., Rotllan, M., & Energy Planning Division Catalan Institute of Energy (ICAEN). (2017, February 22). *Energy challenges in Catalonia from a policy perspective* [Slides]. Https://Climate.Copernicus.Eu/. https://climate.copernicus.eu/sites/default/files/2018-11/05_C3S_Symposium_Villar_and_Rotlan_Feb2017.pdf

Wang, C. N., Lin, W. C., & Le, X. K. (2014). Modelling of a PMSG Wind Turbine with Autonomous Control. *Mathematical Problems in Engineering, 2014*, 1–9. https://doi.org/10.1155/2014/856173

WNA. (2021). *Carbon Dioxide Emissions From Electricity*. World Nuclear Association. https://www.world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity.aspx

Yodwong, B., Guilbert, D., Phattanasak, M., Kaewmanee, W., Hinaje, M., & Vitale, G. (2020). AC-DC Converters for Electrolyzer Applications: State of the Art and Future Challenges. *Electronics*, *9*(6), 912. https://doi.org/10.3390/electronics9060912

Zhang, Y., Sun, H., & Guo, Y. (2020). Integration Design and Operation Strategy of Multi-Energy Hybrid System Including Renewable Energies, Batteries and Hydrogen. *Energies*, *13*(20), 5463. https://doi.org/10.3390/en13205463

7. Appendices.

A. System Structure

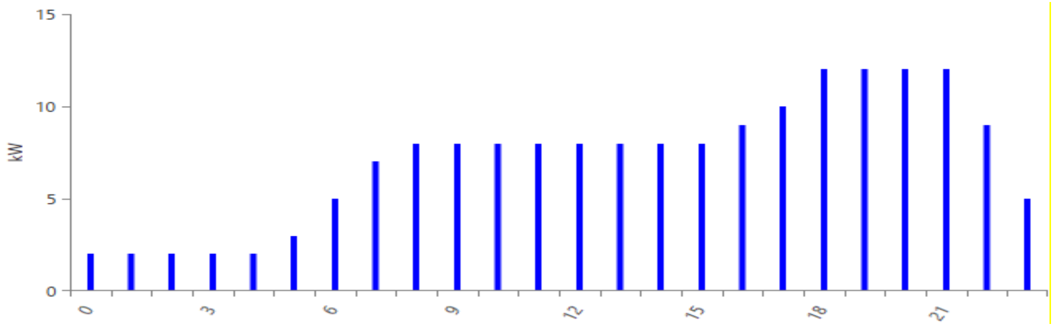


Figure A.1 Daily Load Profile

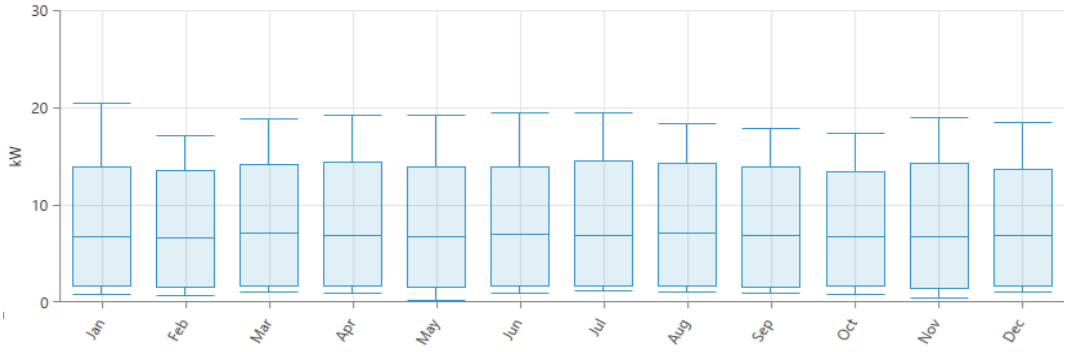


Figure A.2 Seasonal Load Profile

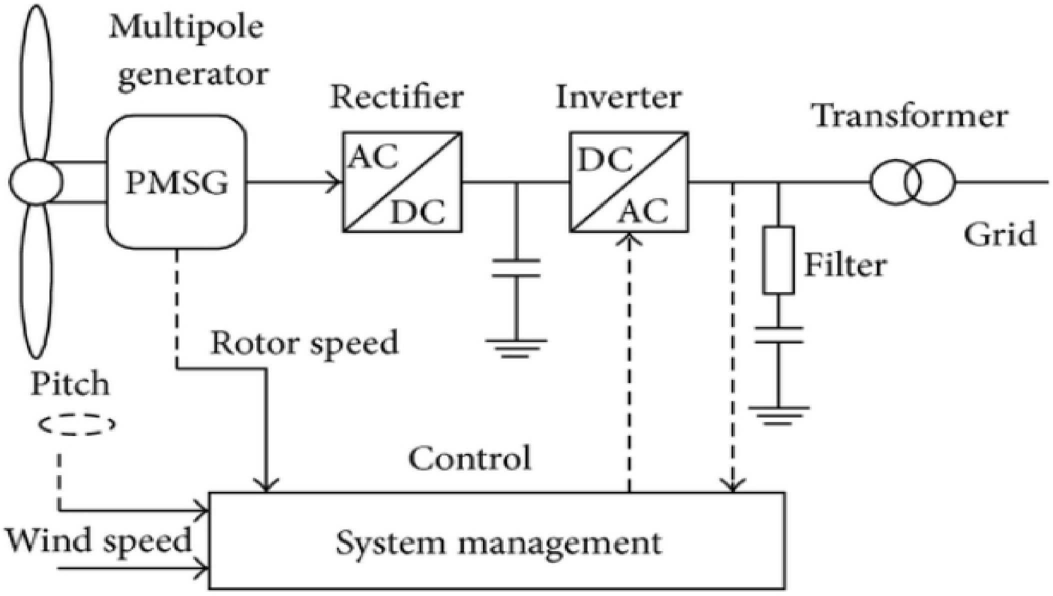
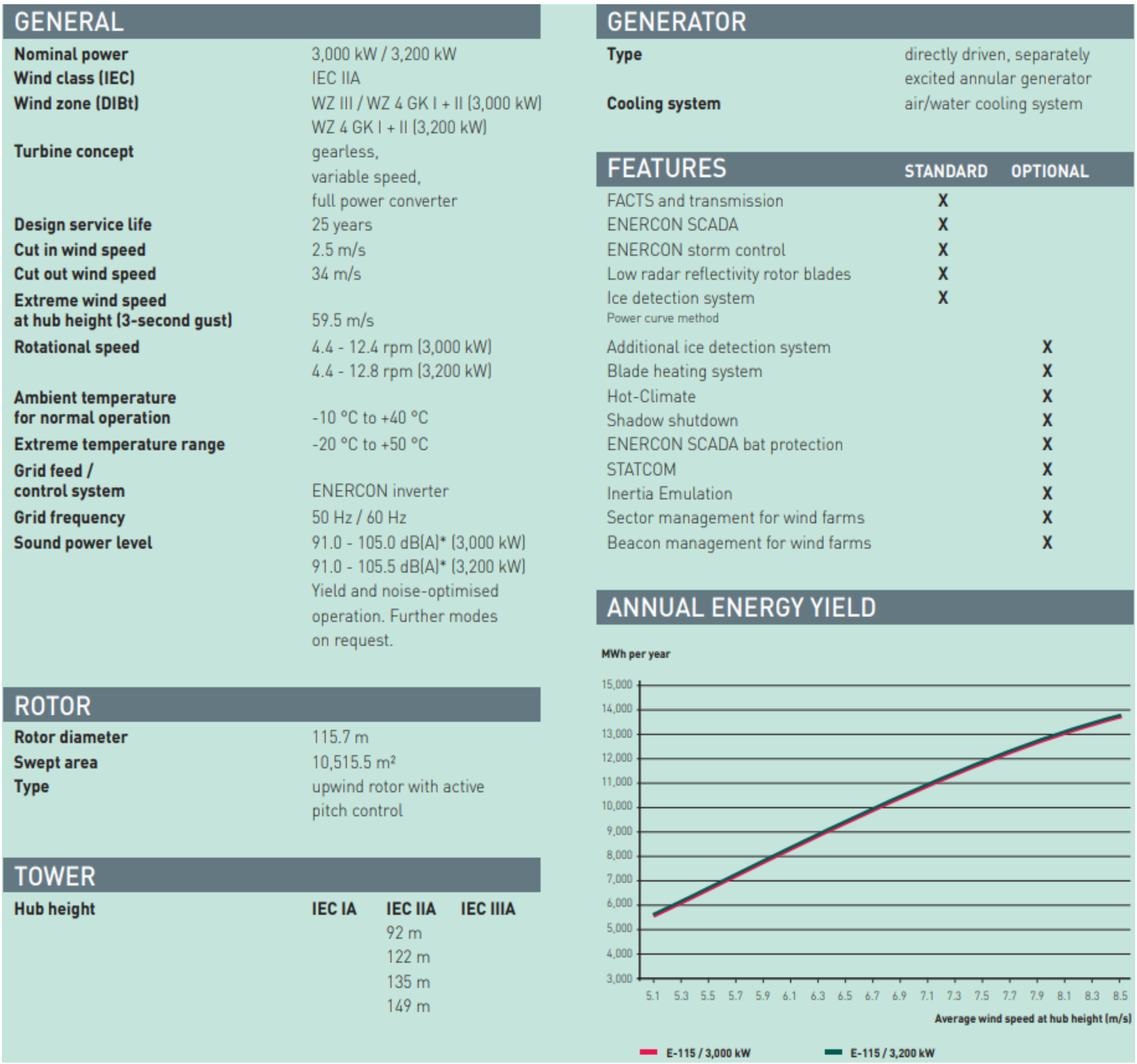


Figure A.3 PMSG Model Schemes (Wang et al., 2014)



GENERAL

Nominal power	3,000 kW / 3,200 kW
Wind class (IEC)	IEC IIA
Wind zone (DIBt)	WZ III / WZ 4 GK I + II (3,000 kW) WZ 4 GK I + II (3,200 kW)
Turbine concept	gearless, variable speed, full power converter
Design service life	25 years
Cut in wind speed	2.5 m/s
Cut out wind speed	34 m/s
Extreme wind speed at hub height (3-second gust)	59.5 m/s
Rotational speed	4.4 - 12.4 rpm (3,000 kW) 4.4 - 12.8 rpm (3,200 kW)
Ambient temperature for normal operation	-10 °C to +40 °C
Extreme temperature range	-20 °C to +50 °C
Grid feed / control system	ENERCON inverter
Grid frequency	50 Hz / 60 Hz
Sound power level	91.0 - 105.0 dB(A)* (3,000 kW) 91.0 - 105.5 dB(A)* (3,200 kW) Yield and noise-optimised operation. Further modes on request.

ROTOR

Rotor diameter	115.7 m
Swept area	10,515.5 m²
Type	upwind rotor with active pitch control

TOWER

	IEC IA	IEC IIA	IEC IIIA
Hub height		92 m	
		122 m	
		135 m	
		149 m	

GENERATOR

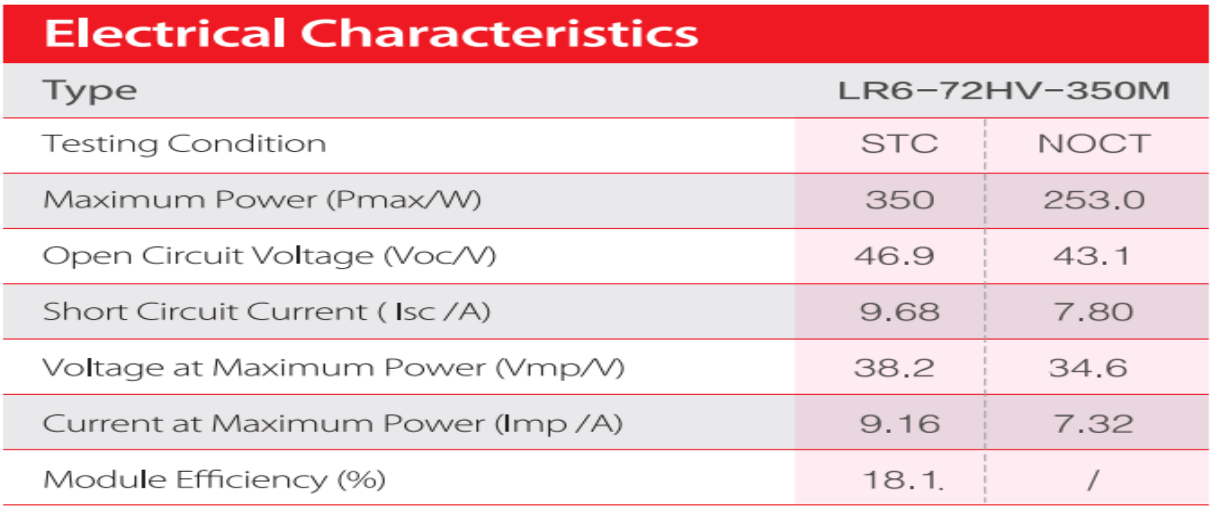
Type	directly driven, separately excited annular generator
Cooling system	air/water cooling system

FEATURES

	STANDARD	OPTIONAL
FACTS and transmission	X	
ENERCON SCADA	X	
ENERCON storm control	X	
Low radar reflectivity rotor blades	X	
Ice detection system Power curve method	X	
Additional ice detection system		X
Blade heating system		X
Hot-Climate		X
Shadow shutdown		X
ENERCON SCADA bat protection		X
STATCOM		X
Inertia Emulation		X
Sector management for wind farms		X
Beacon management for wind farms		X

ANNUAL ENERGY YIELD

Figure A.4 Turbine Characteristics



Electrical Characteristics		
Type	LR6-72HV-350M	
Testing Condition	STC	NOCT
Maximum Power (Pmax/W)	350	253.0
Open Circuit Voltage (Voc/V)	46.9	43.1
Short Circuit Current (Isc /A)	9.68	7.80
Voltage at Maximum Power (Vmp/V)	38.2	34.6
Current at Maximum Power (Imp /A)	9.16	7.32
Module Efficiency (%)	18.1	/

Figure A.5 PV Electrical Characteristics

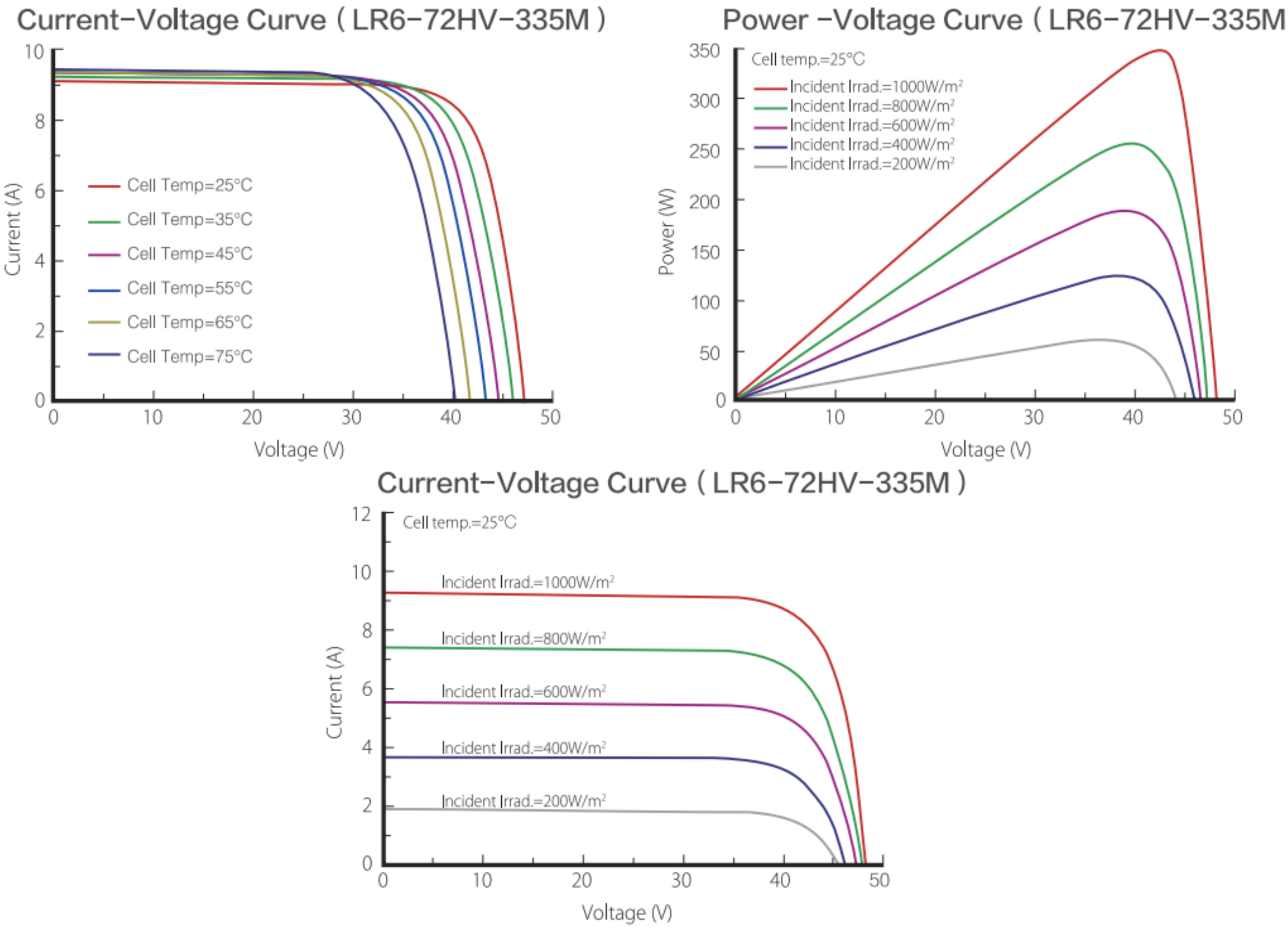
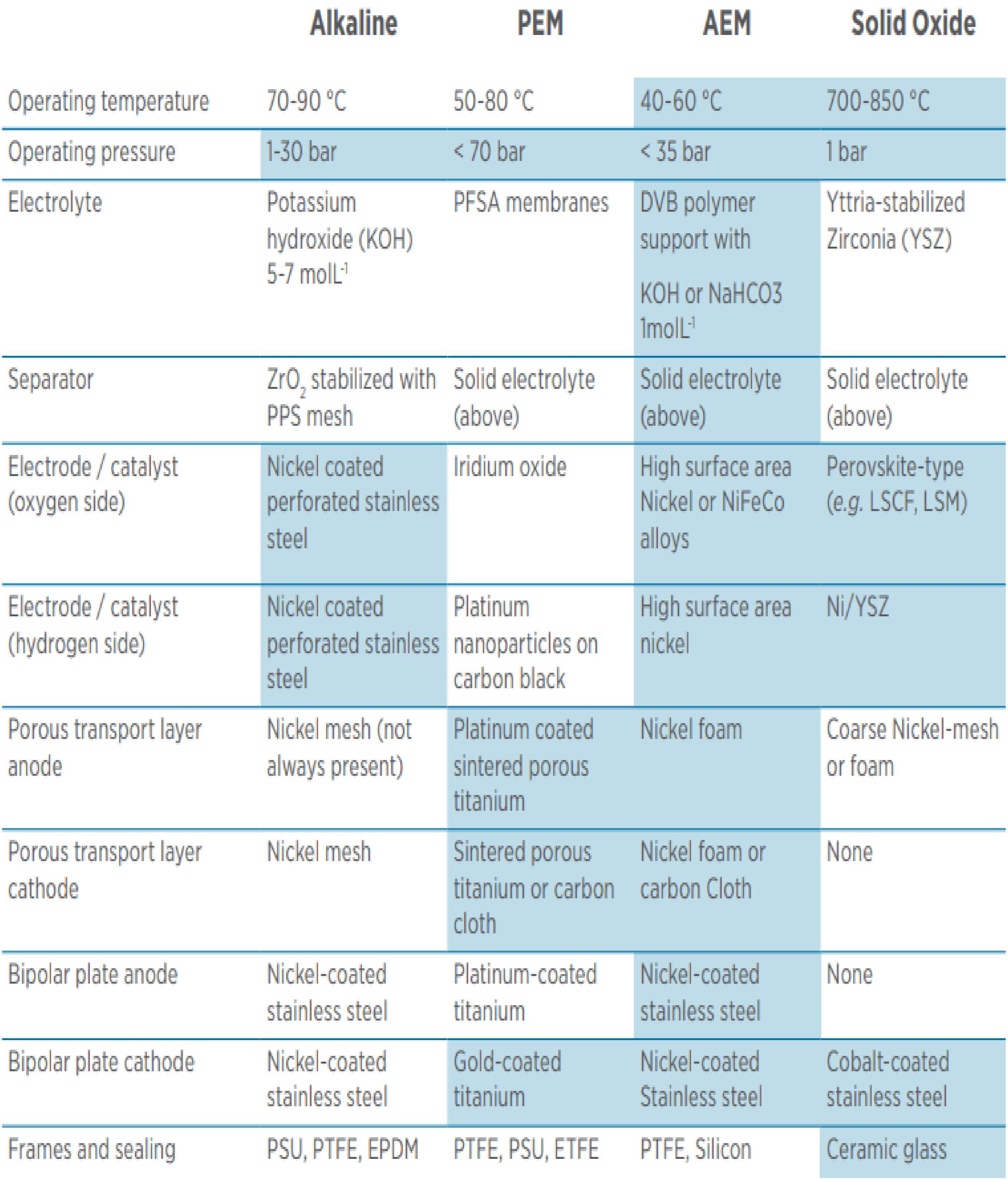
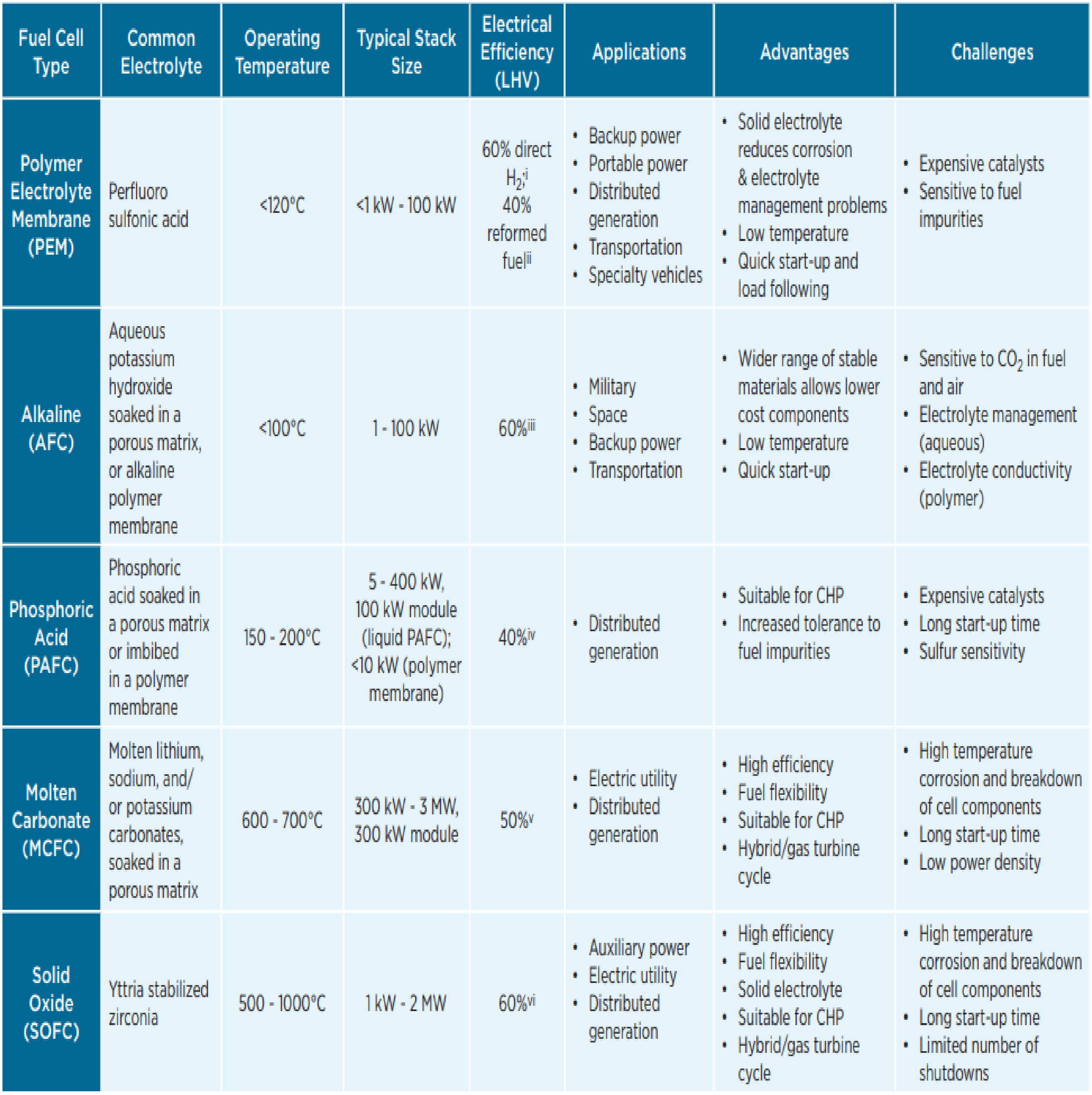


Figure A.6 I-V Curve



	Alkaline	PEM	AEM	Solid Oxide
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 molL^{-1}	PFSA membranes	DVB polymer support with KOH or NaHCO3 1molL^{-1}	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (*e.g.* LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

Figure A.7 Characterization of Electrolysers (IRNA, 2020)



Fuel Cell Type	Common Electrolyte	Operating Temperature	Typical Stack Size	Electrical Efficiency (LHV)	Applications	Advantages	Challenges
Polymer Electrolyte Membrane (PEM)	Perfluoro sulfonic acid	<120°C	<1 kW - 100 kW	60% direct H_2;[i] 40% reformed fuel[ii]	• Backup power • Portable power • Distributed generation • Transportation • Specialty vehicles	• Solid electrolyte reduces corrosion & electrolyte management problems • Low temperature • Quick start-up and load following	• Expensive catalysts • Sensitive to fuel impurities
Alkaline (AFC)	Aqueous potassium hydroxide soaked in a porous matrix, or alkaline polymer membrane	<100°C	1 - 100 kW	60%[iii]	• Military • Space • Backup power • Transportation	• Wider range of stable materials allows lower cost components • Low temperature • Quick start-up	• Sensitive to CO_2 in fuel and air • Electrolyte management (aqueous) • Electrolyte conductivity (polymer)
Phosphoric Acid (PAFC)	Phosphoric acid soaked in a porous matrix or imbibed in a polymer membrane	150 - 200°C	5 - 400 kW, 100 kW module (liquid PAFC); <10 kW (polymer membrane)	40%[iv]	• Distributed generation	• Suitable for CHP • Increased tolerance to fuel impurities	• Expensive catalysts • Long start-up time • Sulfur sensitivity
Molten Carbonate (MCFC)	Molten lithium, sodium, and/or potassium carbonates, soaked in a porous matrix	600 - 700°C	300 kW - 3 MW, 300 kW module	50%[v]	• Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Low power density
Solid Oxide (SOFC)	Yttria stabilized zirconia	500 - 1000°C	1 kW - 2 MW	60%[vi]	• Auxiliary power • Electric utility • Distributed generation	• High efficiency • Fuel flexibility • Solid electrolyte • Suitable for CHP • Hybrid/gas turbine cycle	• High temperature corrosion and breakdown of cell components • Long start-up time • Limited number of shutdowns

Figure A.8 FC Type (EE&RE, 2015)

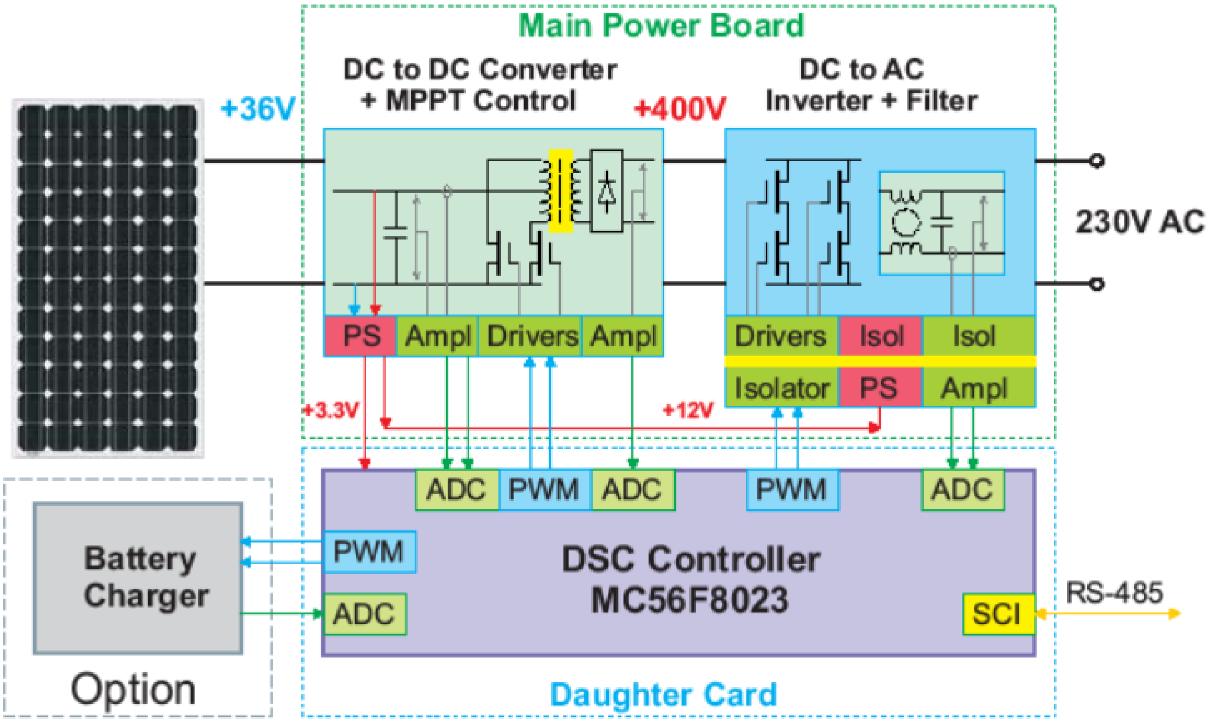


Figure 7.9 Inverter Scheme (NXP, 2011)

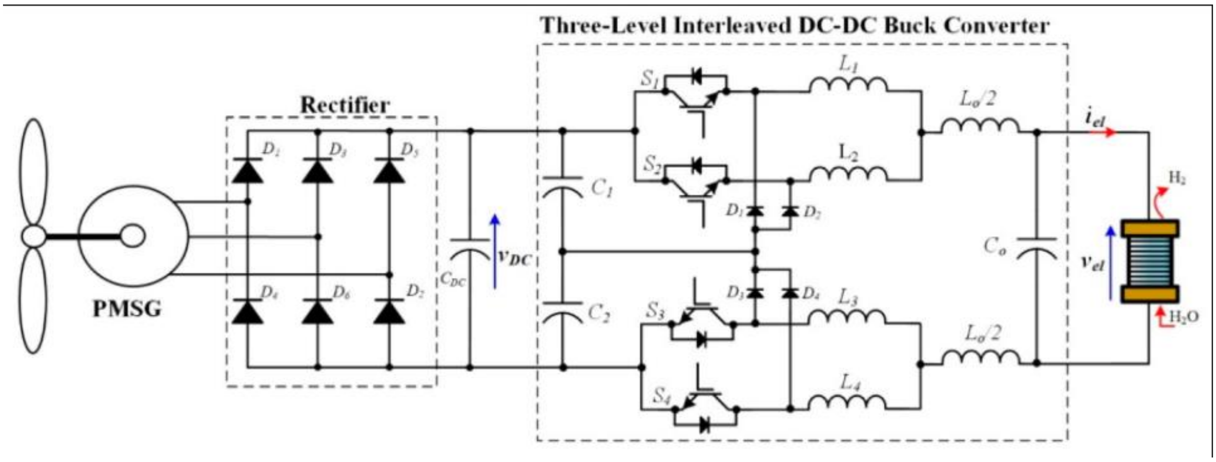
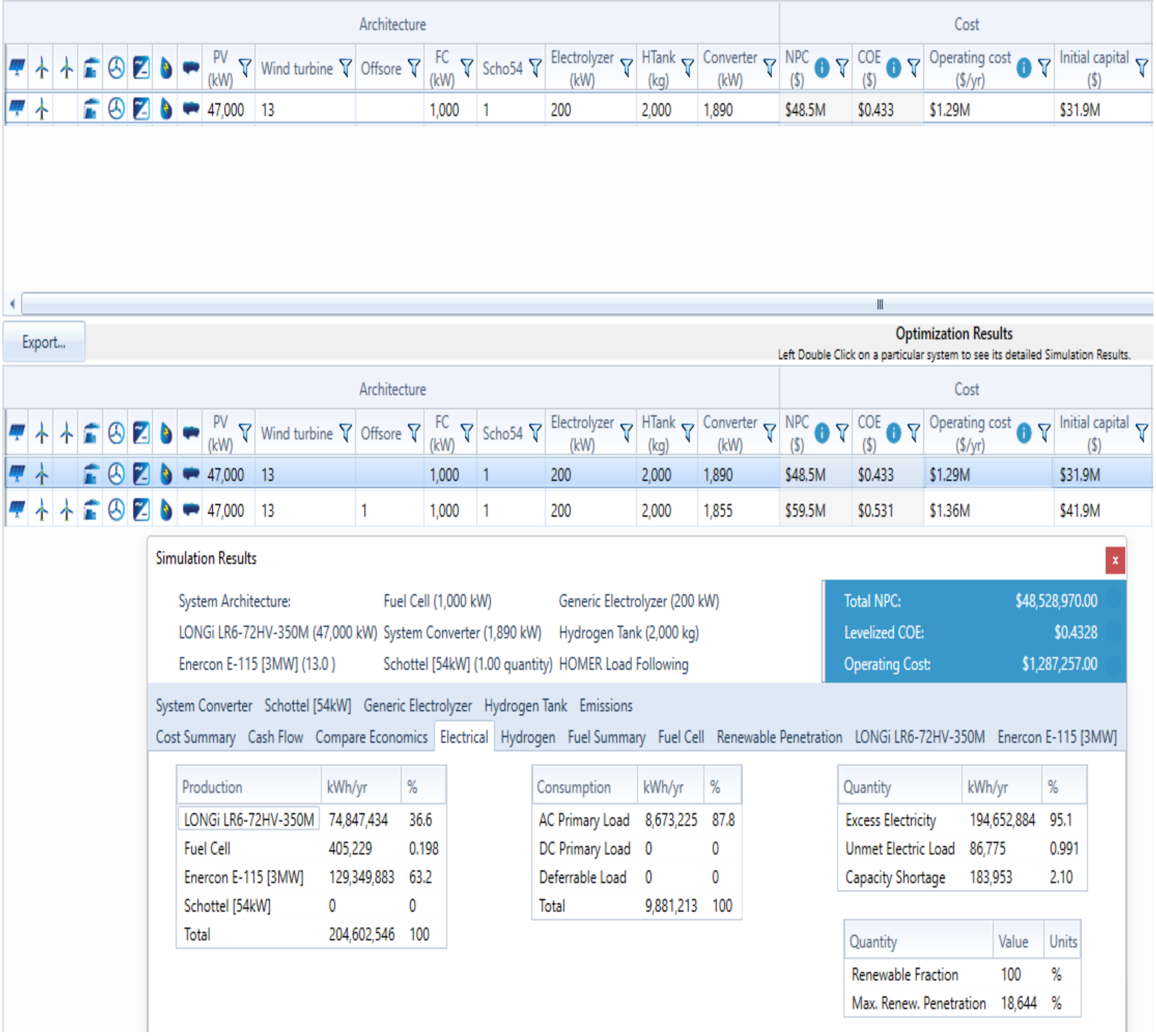


Figure A.10 Rectifier Scheme (Yodwong et al., 2020)

B. Results



Architecture								Cost			
PV (kW)	Wind turbine	Offsore	FC (kW)	Scho54	Electrolyzer (kW)	HTank (kg)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
47,000	13		1,000	1	200	2,000	1,890	$48.5M	$0.433	$1.29M	$31.9M

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Architecture								Cost			
PV (kW)	Wind turbine	Offsore	FC (kW)	Scho54	Electrolyzer (kW)	HTank (kg)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
47,000	13		1,000	1	200	2,000	1,890	$48.5M	$0.433	$1.29M	$31.9M
47,000	13	1	1,000	1	200	2,000	1,855	$59.5M	$0.531	$1.36M	$41.9M

Simulation Results

System Architecture: Fuel Cell (1,000 kW) Generic Electrolyzer (200 kW)

LONGi LR6-72HV-350M (47,000 kW) System Converter (1,890 kW) Hydrogen Tank (2,000 kg)

Enercon E-115 [3MW] (13.0) Schottel [54kW] (1.00 quantity) HOMER Load Following

Total NPC: $48,528,970.00

Levelized COE: $0.4328

Operating Cost: $1,287,257.00

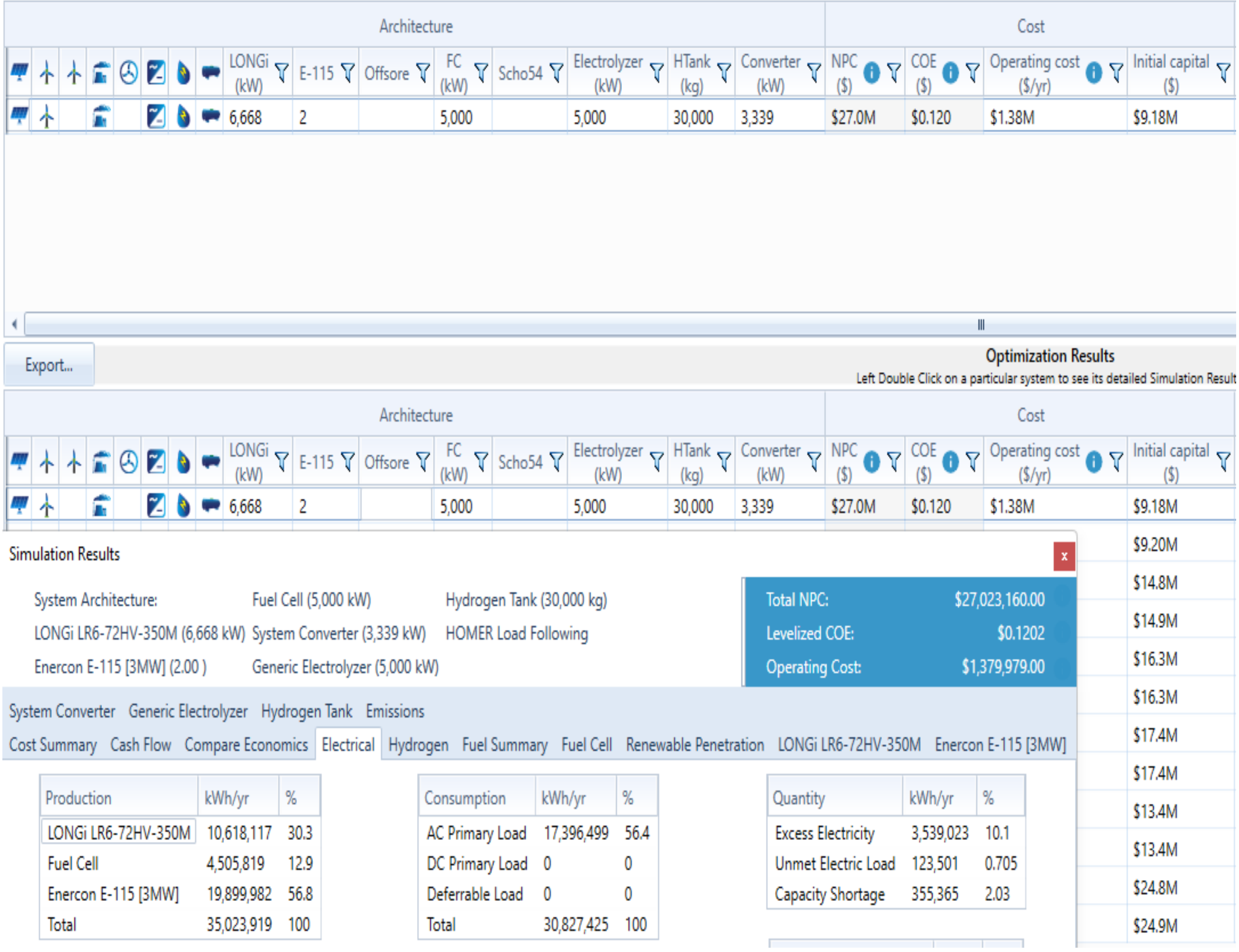
Production	kWh/yr	%
LONGi LR6-72HV-350M	74,847,434	36.6
Fuel Cell	405,229	0.198
Enercon E-115 [3MW]	129,349,883	63.2
Schottel [54kW]	0	0
Total	204,602,546	100

Consumption	kWh/yr	%
AC Primary Load	8,673,225	87.8
DC Primary Load	0	0
Deferrable Load	0	0
Total	9,881,213	100

Quantity	kWh/yr	%
Excess Electricity	194,652,884	95.1
Unmet Electric Load	86,775	0.991
Capacity Shortage	183,953	2.10

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	18,644	%

Figure B.1 1MW MG



Architecture								Cost			
LONGi (kW)	E-115	Offsore	FC (kW)	Scho54	Electrolyzer (kW)	HTank (kg)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
6,668	2		5,000		5,000	30,000	3,339	$27.0M	$0.120	$1.38M	$9.18M

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Result

Architecture								Cost			
LONGi (kW)	E-115	Offsore	FC (kW)	Scho54	Electrolyzer (kW)	HTank (kg)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
6,668	2		5,000		5,000	30,000	3,339	$27.0M	$0.120	$1.38M	$9.18M
											$9.20M
											$14.8M
											$14.9M
											$16.3M
											$16.3M
											$17.4M
											$17.4M
											$13.4M
											$13.4M
											$24.8M
											$24.9M

Simulation Results

System Architecture: Fuel Cell (5,000 kW) Hydrogen Tank (30,000 kg)
LONGi LR6-72HV-350M (6,668 kW) System Converter (3,339 kW) HOMER Load Following
Enercon E-115 [3MW] (2.00) Generic Electrolyzer (5,000 kW)

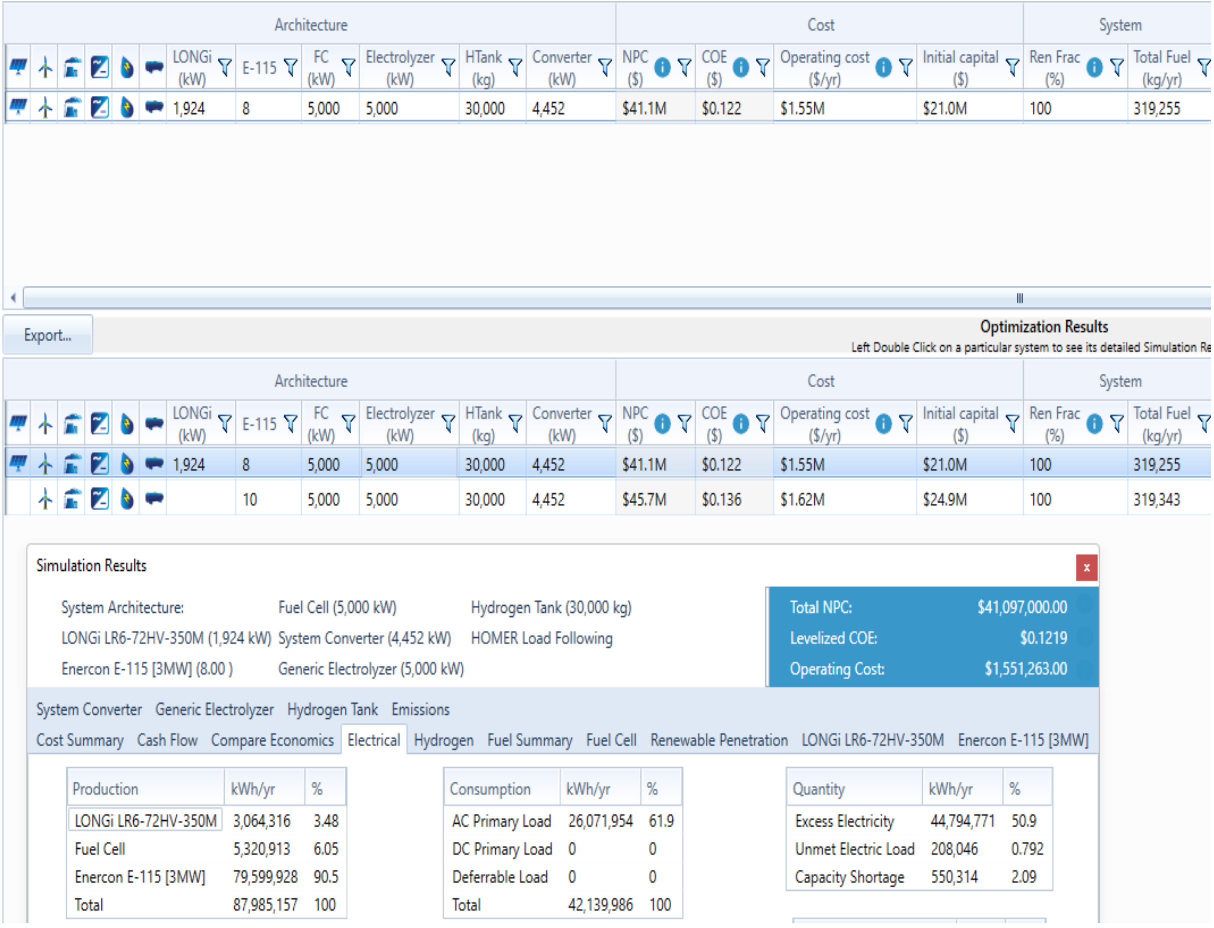
Total NPC: $27,023,160.00
Levelized COE: $0.1202
Operating Cost: $1,379,979.00

Production	kWh/yr	%
LONGi LR6-72HV-350M	10,618,117	30.3
Fuel Cell	4,505,819	12.9
Enercon E-115 [3MW]	19,899,982	56.8
Total	35,023,919	100

Consumption	kWh/yr	%
AC Primary Load	17,396,499	56.4
DC Primary Load	0	0
Deferrable Load	0	0
Total	30,827,425	100

Quantity	kWh/yr	%
Excess Electricity	3,539,023	10.1
Unmet Electric Load	123,501	0.705
Capacity Shortage	355,365	2.03

Figure B.2 2MW MG



Architecture												Cost				System	
						LONGi (kW)	E-115	FC (kW)	Electrolyzer (kW)	HTank (kg)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (kg/yr)
✓	✓	✓	✓	✓	✓	1,924	8	5,000	5,000	30,000	4,452	$41.1M	$0.122	$1.55M	$21.0M	100	319,255

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Re

Architecture												Cost				System	
						LONGi (kW)	E-115	FC (kW)	Electrolyzer (kW)	HTank (kg)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (kg/yr)
✓	✓	✓	✓	✓	✓	1,924	8	5,000	5,000	30,000	4,452	$41.1M	$0.122	$1.55M	$21.0M	100	319,255
	✓	✓	✓	✓	✓		10	5,000	5,000	30,000	4,452	$45.7M	$0.136	$1.62M	$24.9M	100	319,343

Simulation Results

System Architecture:	Fuel Cell (5,000 kW)	Hydrogen Tank (30,000 kg)
LONGi LR6-72HV-350M (1,924 kW)	System Converter (4,452 kW)	HOMER Load Following
Enercon E-115 [3MW] (8.00)	Generic Electrolyzer (5,000 kW)	

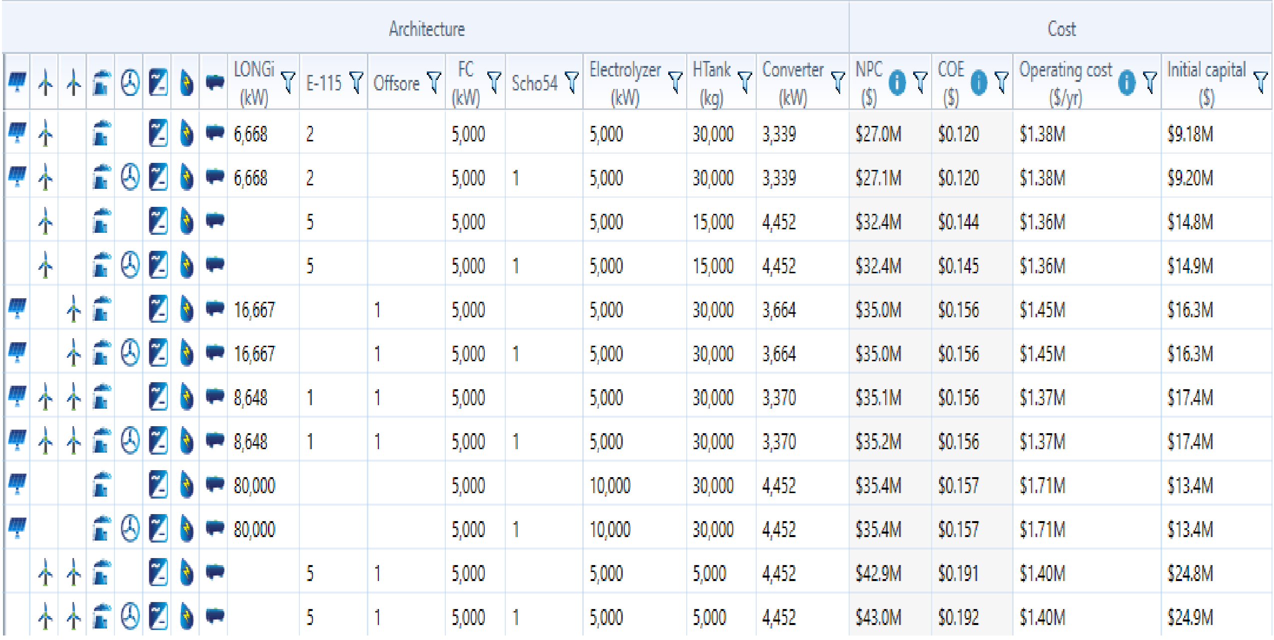
Total NPC: $41,097,000.00
Levelized COE: $0.1219
Operating Cost: $1,551,263.00

Production	kWh/yr	%
LONGi LR6-72HV-350M	3,064,316	3.48
Fuel Cell	5,320,913	6.05
Enercon E-115 [3MW]	79,599,928	90.5
Total	87,985,157	100

Consumption	kWh/yr	%
AC Primary Load	26,071,954	61.9
DC Primary Load	0	0
Deferrable Load	0	0
Total	42,139,986	100

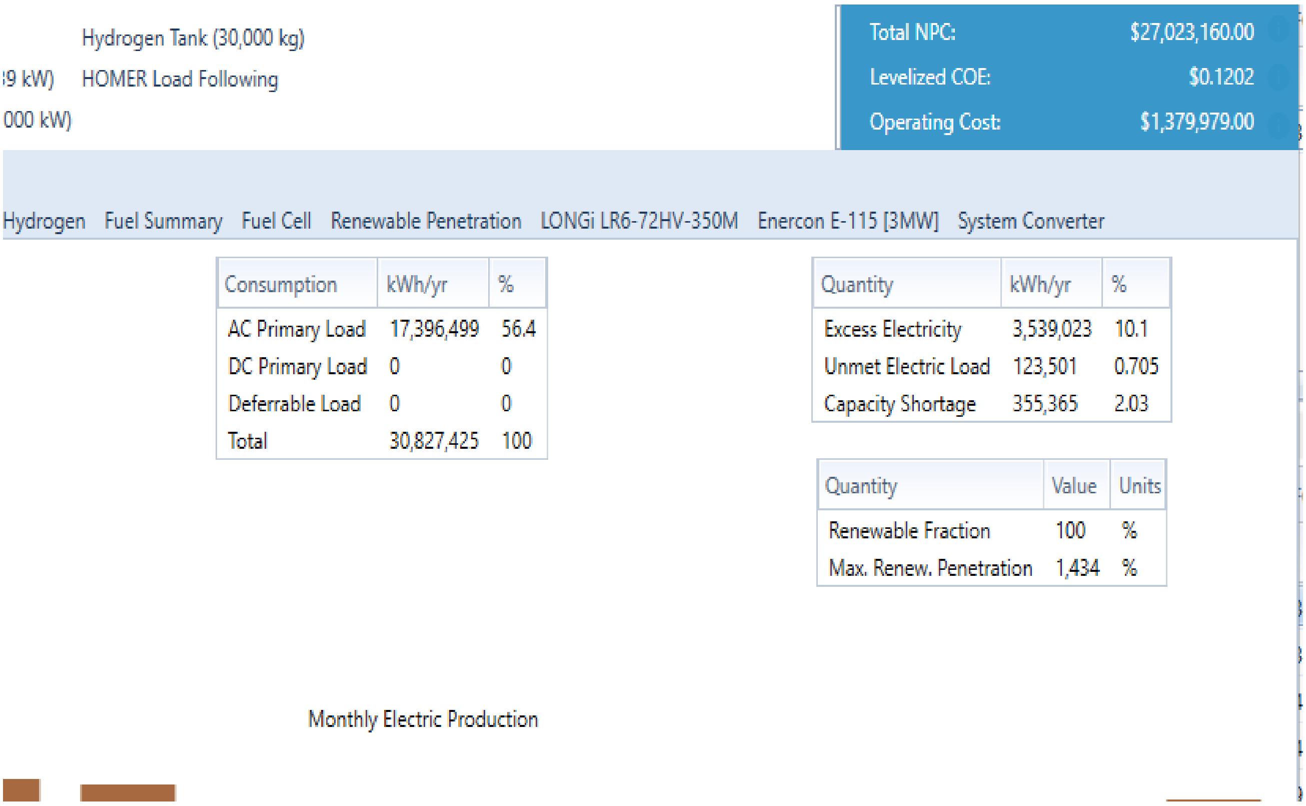
Quantity	kWh/yr	%
Excess Electricity	44,794,771	50.9
Unmet Electric Load	208,046	0.792
Capacity Shortage	550,314	2.09

Figure B.3 3MW MG



Architecture																Cost			
								LONGi (kW)	E-115	Offsore	FC (kW)	Scho54	Electrolyzer (kW)	HTank (kg)	Converter (kW)	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)
✓	✓		✓		✓	✓	✓	6,668	2		5,000		5,000	30,000	3,339	$27.0M	$0.120	$1.38M	$9.18M
✓	✓		✓	✓	✓	✓	✓	6,668	2		5,000	1	5,000	30,000	3,339	$27.1M	$0.120	$1.38M	$9.20M
	✓		✓		✓	✓	✓		5		5,000		5,000	15,000	4,452	$32.4M	$0.144	$1.36M	$14.8M
	✓		✓	✓	✓	✓	✓		5		5,000	1	5,000	15,000	4,452	$32.4M	$0.145	$1.36M	$14.9M
✓		✓	✓		✓	✓	✓	16,667		1	5,000		5,000	30,000	3,664	$35.0M	$0.156	$1.45M	$16.3M
✓		✓	✓	✓	✓	✓	✓	16,667		1	5,000	1	5,000	30,000	3,664	$35.0M	$0.156	$1.45M	$16.3M
✓	✓	✓	✓		✓	✓	✓	8,648	1	1	5,000		5,000	30,000	3,370	$35.1M	$0.156	$1.37M	$17.4M
✓	✓	✓	✓	✓	✓	✓	✓	8,648	1	1	5,000	1	5,000	30,000	3,370	$35.2M	$0.156	$1.37M	$17.4M
✓			✓		✓	✓	✓	80,000			5,000		10,000	30,000	4,452	$35.4M	$0.157	$1.71M	$13.4M
✓			✓	✓	✓	✓	✓	80,000			5,000	1	10,000	30,000	4,452	$35.4M	$0.157	$1.71M	$13.4M
	✓	✓	✓		✓	✓	✓		5	1	5,000		5,000	5,000	4,452	$42.9M	$0.191	$1.40M	$24.8M
	✓	✓	✓	✓	✓	✓	✓		5	1	5,000	1	5,000	5,000	4,452	$43.0M	$0.192	$1.40M	$24.9M

Figure 7.4 Proposed Systems



Hydrogen Tank (30,000 kg)

9 kW) HOMER Load Following

000 kW)

Total NPC:	$27,023,160.00
Levelized COE:	$0.1202
Operating Cost:	$1,379,979.00

Consumption	kWh/yr	%
AC Primary Load	17,396,499	56.4
DC Primary Load	0	0
Deferrable Load	0	0
Total	30,827,425	100

Quantity	kWh/yr	%
Excess Electricity	3,539,023	10.1
Unmet Electric Load	123,501	0.705
Capacity Shortage	355,365	2.03

Quantity	Value	Units
Renewable Fraction	100	%
Max. Renew. Penetration	1,434	%

Figure B.5 Electrical Specification