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Hydropower Advantages over Batteries in Energy Storage of Off-Grid Systems

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Abstract: There has been an ever-increasing demand for energy from the past decades. Renewable energy technologies play a major role in satisfying the energy demand as well as in a decreased CO_2 emissions. Solar and Wind energies are the major upcoming technologies in renewable energies. Decentralized power production is a system where the energy production and consumption are very close to each other. Microgrids can be decentralized or grid connected and they, with renewable energy sources, encounter a problem of storage as the power production from solar and wind is intermittent. This paper discusses the comparison between using batteries and pumped storage hydropower (PSH) as an energy storage system and the integration of wind and solar PV energy sources. HOMER software simulations are used to obtain optimized renewable energy integration in microgrid and to understand its economic analysis. Two scenarios are run with the model where one considers battery and the other considers PSH to obtain the economic and technical best results of these microgrids. The economic analysis showed a lower net present cost (NPC) and levelized cost of energy (LCOE) for the microgrid with PSH. The results show that microgrid with storage of PSH is economical with an NPC of 45.8 M€ and an LCOE of 0.379 €/kWh in comparison with batteries solution which has an NPC of 95.2M€ and an LCOE of 0.786 €/kWh. The role of storage is understood by differentiating the data into different seasons using Python for data analysis. Furthermore, sensitivity analysis is made by varying the capital cost multiplier of Solar PV and Wind Turbine to obtain optimal solutions.

Keywords: hydropower; energy storage; pumped storage hydropower (PSH); batteries; net present cost (NPC); levelized cost of energy (LCOE); microgrids

1. Introduction

Climate change and global warming have been the biggest topics of interest in the current decade. The global electricity demand is expected to reach 30,621 TWh in 2030 and 43,762 TWh in 2050, from 24,700 TWh, which was in 2021, with major part of consumption in buildings and an expected increasing demand from EVs and hybrid industries [1]. Additionally, the invasion of Russia on Ukraine caused energy crisis in many countries. The skyrocketing prices for energy in Europe induced a major burden on consumers, and had a big impact on the economy which was recovering from the COVID pandemic [2]. The net zero emissions and sustainable energy can be achieved with the implementation of different types of Renewables (such as, e.g., Solar Photovoltaics (PV), Wind, Hydropower, Geothermal power, Ocean power, Bioenergy). The total Renewable Energy capacity by the end of 2020 was 2,802 GW [3]. Portugal generated 24.27 TWh of Energy in 2022, accounting for 59.4 % of the total electricity production as shown in Figure 1 which is the distribution of different sources of electricity generation [4].

Hydropower has the highest contribution among all renewable energies. Its capacity is more than the rest of renewable energy technologies combined. 17% of the global electricity was produced by Hydropower in 2020. Figure 2 shows the statistics of the low carbon electricity generating technologies in 2020 [5]. This ability of Hydropower with low carbon electricity and very high generation capacity will be very critical in the journey of the energy transition. Hydropower can be produced in both large and small scales. The large or medium scales typically include the construction of dams and reservoirs to convert potential and kinetic energy into electrical energy, while small scale hydropower can also include energy extraction from water distribution systems and irrigation systems, using existent infrastructures and so adhering to the circular economy concept. Hydropower can also be exploited with the water hammer and PSH technology combined with other renewables such as Solar PV and Wind Energy.[6]

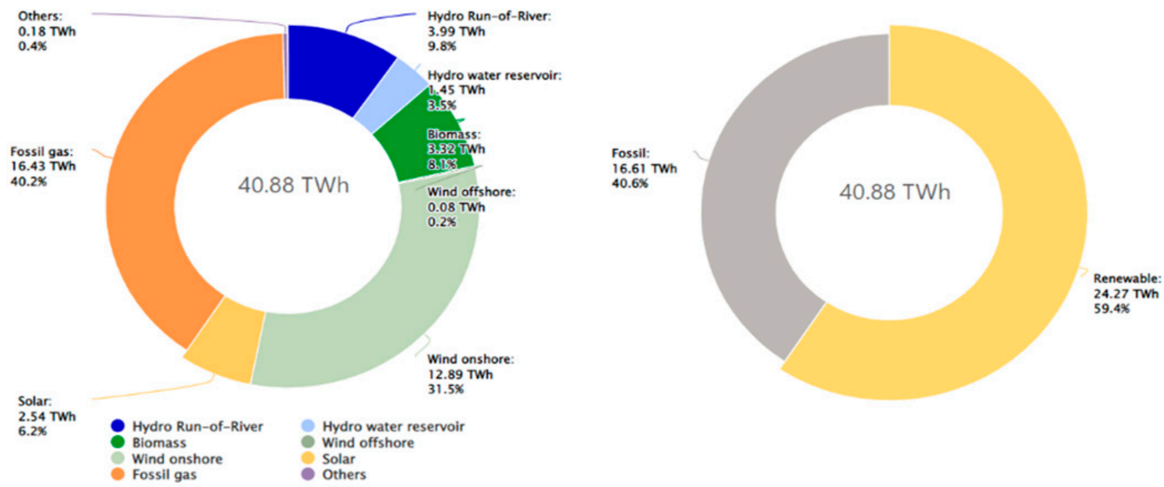

Figure 1. Share of electricity production in Portugal for the year 2022.

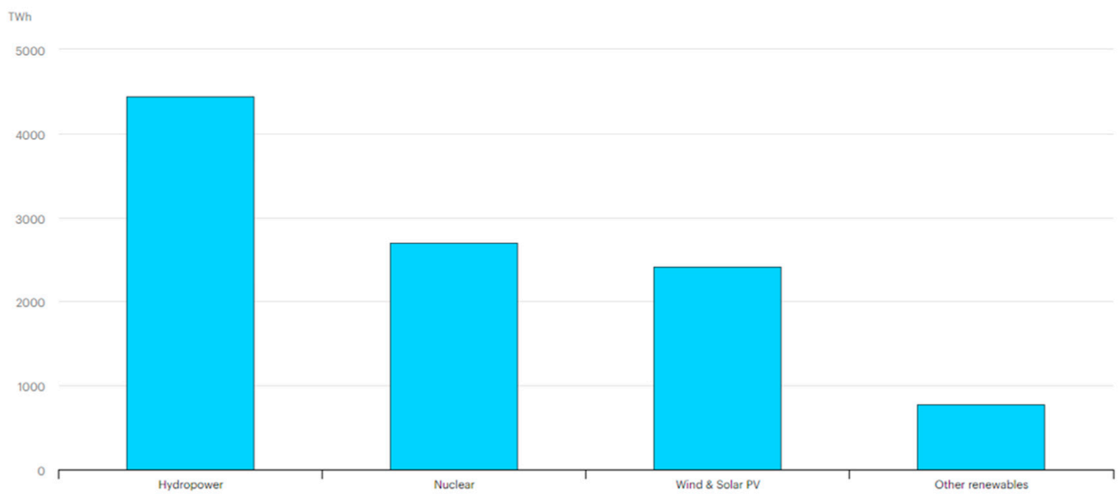

Figure 2. Different technology for electricity generation worldwide with low carbon emissions in 2020.

Decentralized power systems which use only renewable energy systems as energy sources encounter the problem of intermittent energy production from solar and wind and this can be overcome using storage systems. Batteries are one of the excellent energy storage systems which store energy

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chemically. Pumped Storage Hydropower (PSH) is another storage technology which can be used to store energy mechanically. Within this context, this research tries to address the problem of an efficient energy storage technology for mini-grids at remote places and islands. This is a very relevant topic, especially in the European Union. The European Commission is indeed supporting a just and sustainable transition, which means ensuring that regions are not left behind in the clean energy transformation. Besides, the European Commission is committed to ensuring that rural areas benefit from the new economic opportunities from renewable energies. Renewables are well suited for decentralized and local generation by increasing the number of small-scale energy projects to promote sustainable energy production.

The paper's objective is to find the optimum storage technology and have a comparison between Batteries and PSH with respect to their economic evaluation. The economic analysis between PSH and Batteries in Microgrids is done using HOMER software which gives an optimum result with lowest Net Present Cost (NPC) for Microgrids, for a given load scenario of a particular location. PSH uses water resources to store it physically and is run by a turbine to generate electricity. The water is pumped to an upper reservoir when there is excess of electricity production from other renewable resources. The batteries store the energy chemically and Li-ion batteries are efficient battery technologies which are used in current days. The economic scenario of PSH is chosen and a technical analysis is done by separating the result data into different seasons using Python data analysis and the role of PSH as storage is explained. This research further analyzes the sensitivity cases considering different capital cost of solar PV, wind turbine and PSH.

1.1. Pumped Storage Hydropower (PSH) for medium and large-scale energy storage and production

PSH can be considered as a big battery bank which stores water at higher elevation with respect to a lower reservoir or water body. Whenever there is a demand for electricity, water is discharged from upper reservoir to the lower reservoir. The water discharged from the upper reservoir runs a hydro turbine that generates electricity. Whenever there is a surplus of electricity produced from renewables such as wind or solar or when the electricity demand is low, the water is pumped back from the lower reservoir to the upper one. This method of energy storage becomes very critical in off-grid energy systems when there is a dearth of power production from renewables in a low sunshine or a low-speed wind condition which cannot satisfy the demand of electricity. The electricity produced can be controlled by varying the flow to the turbine according to the electricity demand.

The world's largest battery technology is pumped storage hydropower, which accounts for more than 94% of installed global energy storage capacity [8].There are two ways in which PSH can be effectively used for storage. In open loop PSH, the water from a natural body is used to fill one of the two reservoirs and an upper reservoir is used to store the pumped water. In the closed loop, PSH does not have any connection to natural water body and has connection between two reservoirs (upper and lower) only. The environmental impact of an open loop PSH towards the aquatic and terrestrial habitat is more than that of the closed loop PSH, because also the natural river is affected [7]. Closed loop PSH is used in the current research for HOMER simulations.

In 2022, the total installed turbine power capacity from PSH in Portugal was 3.71 GW, and Figure 3 shows the weekly average electricity production in Portugal using different resources and shows the contribution of PSH in the total electricity generation [9].

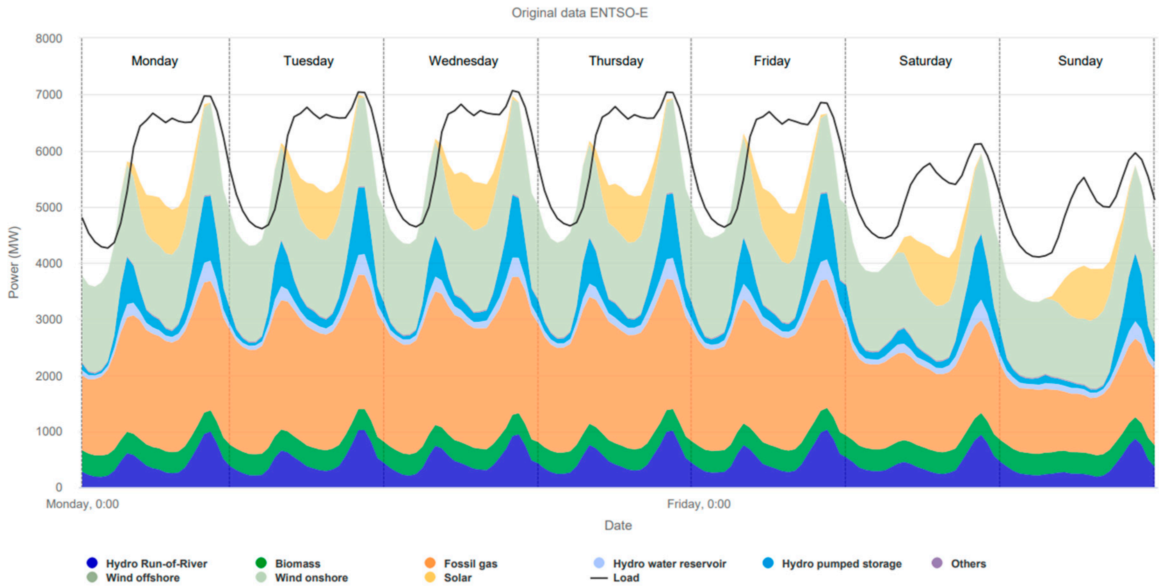

Figure 3. Average total net electricity generation during one week in Portugal in 2022.

1.2. Batteries as storage in Microgrids or off-grids

Batteries are the chemical energy storage technologies that have been revolutionizing the world with their storage capabilities in grids, mobility, electronic gadgets, and many more. The critical factors to consider in a battery are its efficiency, its life cycle time, the temperature of the operation, depth of discharge (DOD), density of energy and self-discharge [10]. There are different classifications of technologies based on the chemistry of the battery such as Lead Acid batteries, Li-ion, Nickel Cadmium, Sodium-Sulphur, Vanadium redox, and much more. The study in [11] analyses the different types of batteries for energy storage and concludes by saying that sodium-sulfur batteries are used in large-scale storage systems, and the production cost of Li-ion and sodium-sulfur batteries are very high in comparison with other battery technologies. However Li-ion batteries have a high efficiency, high energy density and also a longer life cycle which makes them a potential energy storage system for grid application (both off-grid and on-grid) [12]. Lead acid batteries are also the potential competitors for energy storage in off- grids and microgrids due to their low cost. When Lead acid batteries are compared with Li-ion batteries, Li-ion batteries show a longer life cycle, greater efficiency, a better charging and discharging cycles, although the upfront cost of Lead acid batteries seems to be lesser than Li-ion batteries but over the lifetime of the batteries, Li-ion batteries come out to be the economic option [13].

1.3. Microgrids or Decentralized Power Production

There are several constraints in extending energy access to remote places and islands as this will be a problem economically and will also cause environmental impacts. Decentralized power production with distributed energy resources is a promising system where power generation and consumption exist at the same place. This system can have zero emissions by using renewable sources only. Wind and Solar can be the major resources for the production of electricity, however, the problem of intermittency of power production in Solar PV and Wind Energy is a major problem to use only renewables as a source for satisfying the demand. Therefore, the usage of Energy storage technologies such as Batteries and PSH becomes inevitable to satisfy the continuous demand for electricity. Batteries and PSH come with their pros and cons when used as storage technology. Reference [14] gives an overview of the different software that can be used for the design of hybrid energy systems. A hybrid renewable energy system (HRES) is one where there is a combination of more than one energy source [15]. The HOMER is a software tool that is used to design power systems which is developed by the National Renewable Energy Laboratory of the US. The software can be used to design

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microgrid systems using various energy generation technologies with the resources that can be taken from a specific geographic location. The software performs simulation, optimization and sensitivity analysis. The simulation is done to consider the technical aspects and life cycle costs and the optimization of HOMER selects the scenario that satisfies the technical aspects with least cost over the period of project. The sensitivity analysis takes care of the uncertainties and performs a range of simulations and optimization considering the variability in inputs [16]. Table 1 shows the different researches that are studied on HOMER software.

Table 1. Different research on microgrids using HOMER software at different locations.

Paper	Optimal Energy System	Location	Economics
Demiroren and Yilmaz (2010) [17]	Wind Energy System (PV/Battery)	Gokceada, Turkey	NPC : 32, 537, 056 $ LCOE : 0.174 $/kWh
Yimen et al. (2018) [18]	PV/Biogas/PSH	Djoundé, Cameroon	NPC : 370,426 € LCOE : 0.256 €/kWh
Dalton et al. (2009) [19]	Wind Energy System with Battery	Coastal area of Queensland, Australia	NPC : 19.1 M$
Ioakimidis et al. (2016) [20]	Scenario 1 : Generator/ wind energy/ Battery Sceanrio 2 : Wind/Solar PV/ generator/Battery Scenario 3 : Wind/PV/Battery	An Island in Greece	NPC : 1,834,996 € LCOE: 0.1658 €/kWh NPC : 2,249,666 € LCOE: 0.2047 €/kWh NPC : 6.5 million € LCOE: 0.61 €/kWh
He et al. (2018) [21]	Stand alone: Solar PV/Wind Energy/ Battery/Diesel Generator Grid Connected : Solar PV/Wind Energy/ Battery/ Grid	Beijing, China	NPC : 16,806,238 $ LCOE: 0.133 $/kWh NPC : 9034,966 $ LCOE : 0.055 $/kWh
Sen and Bhattacharyya (2014) [22]	Solar PV/Wind Energy/Battery/Bio-Diesel Generator/Hydropower	Chhattisgarh, India	NPC: 673,147 $ LCOE : 0.420 $/kWh

1.4. Data Preparation and Cleaning of the obtained load data

The load data is obtained for each hour from the REN website source [23] of Portugal country and is scaled down to obtain the load suitable for the analyzed microgrid. The load data obtained from the website are further used in the simulations of the HOMER software. The quality of data is enhanced by identifying and clearing the error and data that are not consistent [24]. There can be different types of data, but quantitative data are the data that can measure the topic of interest with numbers such as integers or decimals, and consistent data will result in a reliable analysis of data [25]. To avoid any sort of unwanted results where there is a usage of data, the data has to be cleaned first before using it. With the use of Python language for data analysis, the load data that is obtained from the REN website is prepared. The zero and missing value of power is replaced by the average

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value of power consumption. The duplicate values from the collected data are removed in the data preparing process. Outliers are the data that are significantly deviating from the normal value or the pattern in the obtained data.

2. Methodology

The Design of a DER (Distributed Energy Resource) system requires a careful analysis of the available resources in the desired location to install the renewable energy systems. Microgrids/Mini-grids will become critical in providing energy to remote places and islands where the grid extension is not feasible. Constructing a framework that unifies all the available renewable energy systems without compensating the reliability of the system is quite challenging. Energy storage systems play a crucial role in the decentralized energy systems.

The simulation of the Decentralized Energy Systems/Renewable Energy Systems can be done with many software such as HOMER, PVsyst, and others. HOMER software is used in the current research to obtain optimal results. The HOMER software uses the load data given and collects the resource data from the location where to install the microgrid. The HOMER results show the economic feasibility of the projects. The results from the HOMER calculations show the Net Present Cost (NPC), Levelized Cost of Energy (LCOE), Operation and Maintenance costs (O & M) and Autonomy of Storage. There are two scenarios explained in this research that are simulated in the HOMER and Phyton softwares. The scenarios compare the costs of using the batteries and pumped storage hydropower with the given load and renewable energy resources. The further sections explain the details of components and simulations characteristics.

2.1. Load

The Load for the current system which is used for the optimization model is taken from the hourly consumption data of Portugal with the source of the REN website. The Electric loads are the power consumed every hour in kW. Hourly data are very important in running scenarios to get accurate results. The data is taken concerning the comparison of Batteries and PSH as energy storage solution and analyze the cost and feasibility aspects of it. Figure 4 shows the graph of the load. The peak load is 1591.08 kW the average energy consumed is 25,670.35 kWh/day. The load factor of 0.33 is considered for both simulations. The load is low during the months of Summer as there will be no heating required.

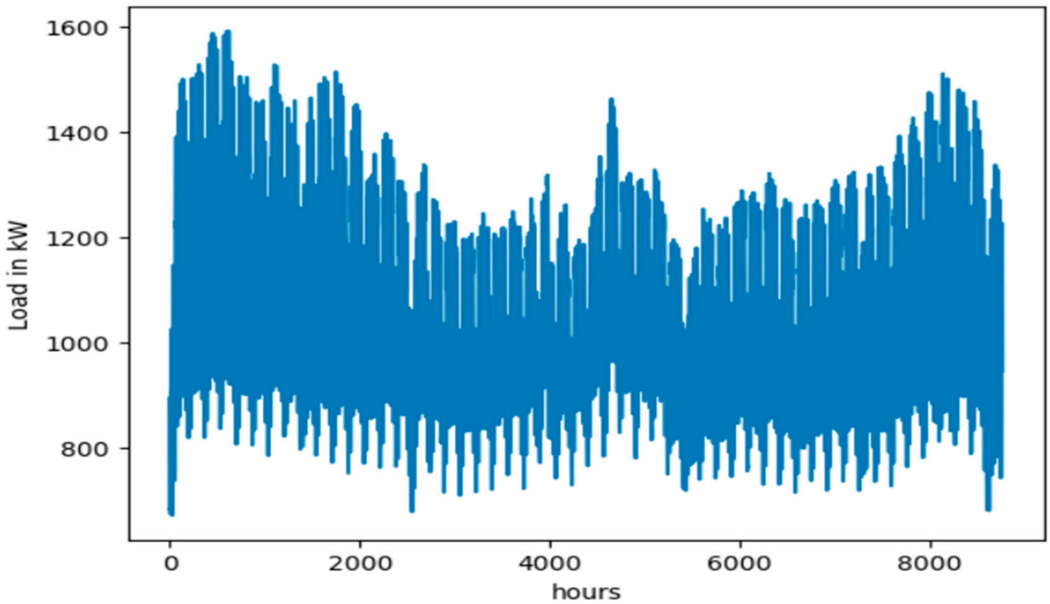

Figure 4. Hourly load distribution in kW throughout the year 2022.

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2.2. Resources

The location used for the HOMER simulations is the Madeira Islands in Portugal. The HOMER software downloads the data of solar irradiance, windspeed, and temperature data from different sources such as NREL or NASA satellites. Portugal is in the southern part of Europe and gets much higher solar power in comparison with the northern countries of Europe.

Figure 5. Map of the location for simulations.

2.2.1. Solar Energy Data

The Solar irradiation data is taken from the NASA Prediction of Worldwide Energy Resource (POWER), in the specified location, where the annual average daily radiation is 5.12 $\frac{\mathrm{kWh}}{\mathrm{m}^2}$/day. Figure 6 shows the distribution of the solar data in different months. The peak daily radiation is seen in the month of July with 7.22 $\frac{\mathrm{kWh}}{\mathrm{m}^2}$/day. The lowest daily radiation is in the month of December with 2.580 $\frac{\mathrm{kWh}}{\mathrm{m}^2}$/day. The clearness index shows the clearness in the sky. The portion of incoming radiation that incidents on earth is the clearness index. The higher the clearness index value, the greater will be the available energy to convert it to electricity [26]. The highest clearness index is in the month of August with a value of 0.663 indicating that there are many clear sky days in that month, whereas the lowest clearness index is in the month of December with a clearness index of 0.510 indicating that there are many cloudy days in the month.

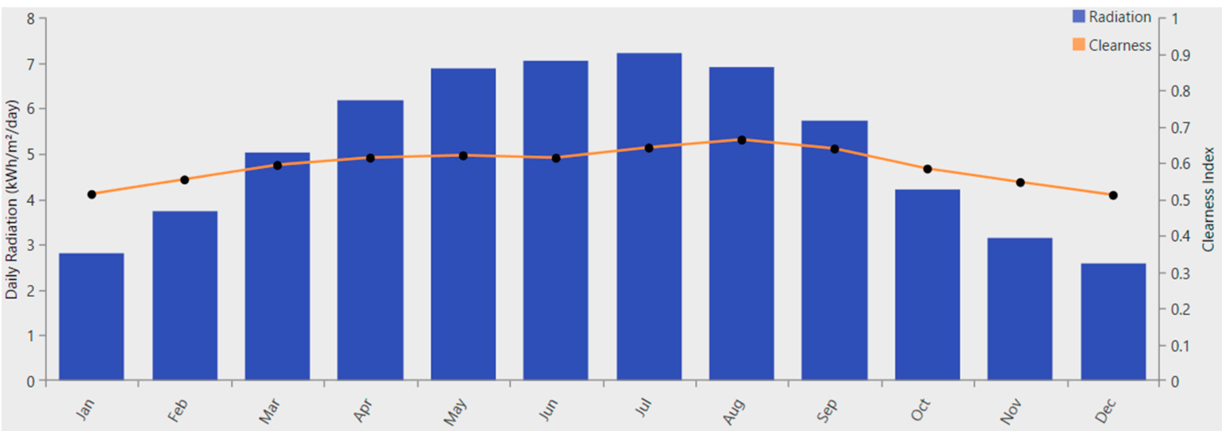

Figure 6. Solar Radiation data of the location with radiation in kWh/m^2/day for different months of an average year and with the clearness index for different months.

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2.2.2. Wind Energy Data

The HOMER software collects the windspeed data from the NASA POWER database. Figure 7 shows the distribution of wind speeds in different months of the year. The anemometer measures the windspeeds at a height of 10 m. The wind data is of 50 m altitude above sea level and measured over a period of 30 years. The average annual windspeed is 6.42 m/s. The highest wind speed is seen in the month of December with an average speed of 7.10 m/s. The lowest wind speed is in September with a wind speed of 5.369 m/s. The optimized model considers for the wind speed data is that the surface roughness length is 0.01m. Figure 8 shows the graph of windspeeds with the hub height. The windspeed at a specific height can be calculated using the Prandtl law as shown in equation (1).

$$\frac{u(z1)}{u(z2)} = \frac{ln\left(\frac{z1}{z0}\right)}{ln\left(\frac{z2}{z0}\right)} \tag{1}$$

where,

u = average wind speed

z0 = surface roughness

z1= height 1

z2= height 2

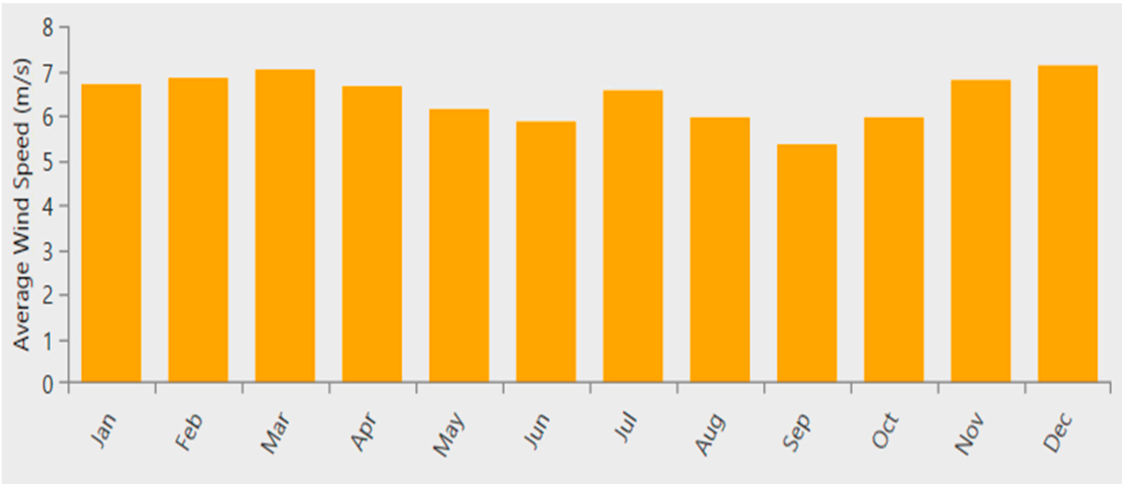

Figure 7. Average wind speed for all the months considering roughness length of 0.01m and windspeeds measured at a height of 10 m.

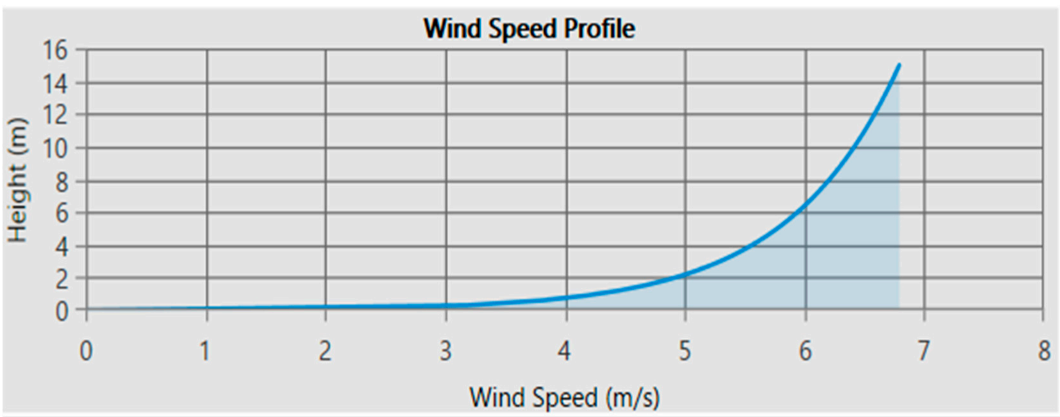

Figure 8. Variation of windspeed with different windspeeds considering the roughness length.

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2.3. Basic Terminologies

2.3.1. Net Present Cost (NPC)

The Net Present Cost is the difference between the current value of all the costs including operation and maintenance costs, replacement costs for the lifetime of the project and the present value of the revenue the project earns over its entire lifetime. The projects should be designed in such a way to reduce the Net Present Costs [27]. HOMER uses the discount rate to calculate the NPC. The Net Present Cost can be calculated using the following formula [28] with

$$NPC = \frac{TAC}{CRF} \quad (2)$$

$$CRF = \frac{i(1+i)^N}{(1+i)^N} \quad (3)$$

where,

TAC = Total annualized cost
CRF = Capital Recovery Factor
N = Number of Years
i = Annual Interest rate (%)

2.3.2. Levelized Cost of Energy (LCOE)

Levelized Cost of Energy is the ratio of average cost of electrical energy produced and the Electrical Energy produced by the system. This can be calculated using the following equation [29]:

$$LCOE = \frac{C_{ann,tot}}{E_{served}} \quad (4)$$

where,

$C_{ann,tot}$ = total annualized cost, in EUR
E_{served} = Total Electric load served

2.3.3. Operation and Maintenance Cost

The operation and maintenance costs are the costs associated with the wear and tear of the equipment such as Wind Turbine, Solar PV, Hydropower equipment. These can be variable or fixed costs associated with the project. These usually cover the maintenance of dams in Hydropower, Hydro Turbines and other equipment in Wind Turbines. HOMER receives the O&M (Operation and Maintenance) costs for different systems as input and calculates the total O&M cost of the system over the complete cycle of the project [30].

2.3.4. Autonomy of the Storage

Autonomy can be defined as the physical quantity of time which can serve the load in the absence of an energy source. These are measured in hours or days. A higher autonomy of storage will increase the reliability of the Energy system by serving the load. Autonomy of storage is an important factor which serves as a backup power for the energy system that is installed and covers the variations in lower power productions to keep the system up and running.

2.4. Simulations

There are two simulation scenarios done in this research in order to find the optimum feasibility of the project with respect to economics and later a comparison of economic assessment is also done. The HOMER software optimizes different scenarios to suggest the lowest NPC scenario. The paper concentrates on two scenarios where in Scenario 1, Solar PV, Wind Turbines and Batteries are used to meet the electrical load demand as shown in Figure 9. In Scenario 2, Solar PV, Wind Turbines and Pumped Storage Hydropower is used to meet the electrical load as shown in Figure 10. The electric

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load is same for the both scenarios and same company PV and Wind turbines are used without altering the costs in both scenarios in order to get suitable comparison.

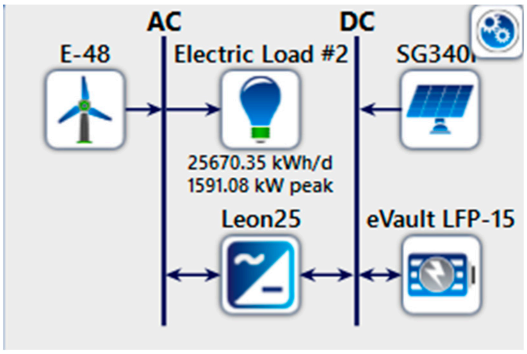

Figure 9. Scenario 1 with Wind Turbine, Solar PV and Battery as storage.

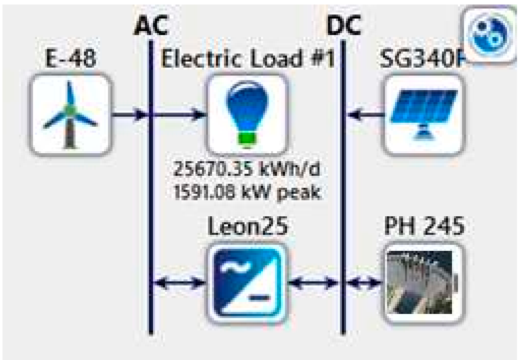

Figure 10. Scenario 2 with Wind Turbine, Solar PV and PSH as storage.

2.4.1. Solar PV

Solar PV is an economic source of power when designing a Renewable Energy based Microgrid system. Table 2 shows the specifications of the Solar PV used for the simulations. The costs for the solar PV are considered as 3000€/kW with a replacement cost of 3000€/kW and an Operation and Maintenance cost of 10€/kW. Peimar SG340P is a multi-crystalline Solar PV and the efficiency of the monocrystalline solar PVs is more than the multi-crystalline Solar PVs, however, the cost for monocrystalline is higher as well. The power from the Solar PV can be calculated using the equation (5).

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}}\right)[1 + \alpha_P (T_c - T_{c,STC})] \quad (5)$$

where,

Y_{PV} = Power output during standard test conditions in kW.
f_{PV} = Derating factor of solar PV
G_T = Incident solar irradiance in kW/m^2.
$G_{T,STC}$ = Incident solar irradiance at Standard test conditions which is 1 kW/m^2.
α_P = temperature co-efficient of power.
T_c = Cell temperature of solar PV in °C.
$T_{c,STC}$ = Cell temperature under standard test conditions which is 25 °C.

2.4.2. Wind Turbine

Wind Turbines are one of the major renewable energy converting systems in Europe. The wind turbine used in the simulation is Enercon E-48 with a capacity of 800kW. The Figure 11 shows the annual energy yield of the wind turbine with the variation of the windspeed [31]. The cost for the

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wind turbine is considered to be 3800€/kW with an operation and maintenance cost of 25,600€/ year [32]. The turbine specifications are given in the Table 2 [31]. HOMER calculates the power produced by the wind turbine by calculating the power at hub height with the power curve and then multiplies the power produced with air density ratio.

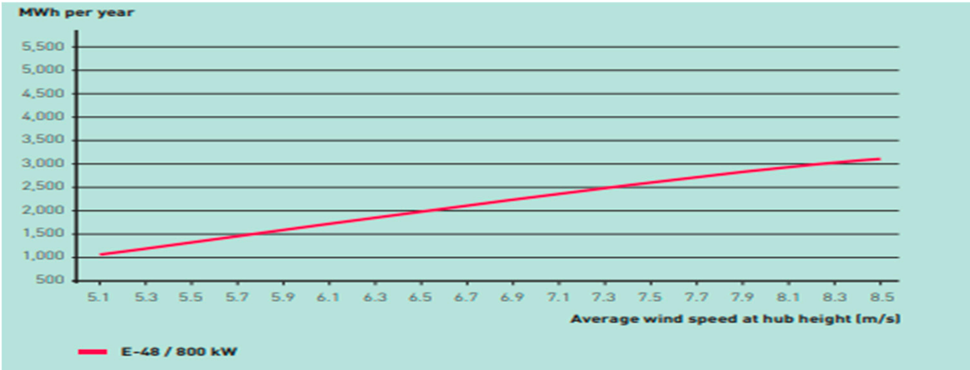

Figure 11. Annual Energy yield of Enercon E-48 wind turbine.

Table 2. Technical Specifications of all the renewable energy systems used.

Solar PV - Peimer SG340P		**Wind Turbine - Enercon E-48 [800kW]**	
Parameters	**Value**	**Parameters**	**Value**
PV Model	Peimar SG340P	Wind Turbine Model	Enercon E-48
Vmp	38.3 V	Rated Capacity	800 kW
Imp	8.88 A	Rotor Diameter	48m
Rated Capacity	1500 kW	Cut-in windspeed	2.5 m/s
Efficiency	17.5	Cut-out windspeed	34 m/s
Operating Temperature	25 °C	Generator	Direct Driven Generator
Temperature Coefficient	-0.43		

Convertor - Leonics MTP-413 F		**Battery - Fortress Power eVault LFP-15 Battery**	
Parameters	**Value**	**Parameters**	**Value**
Inverter Model	Leonics MTP-413F 25kW	Nominal Voltage (V)	48
External DC charger	240V	Nominal Capacity (kWh)	14.4
Phase	3 phase	Nominal Capacity (Ah)	300
Maximum efficiency	95%	Roundtrip efficiency (%)	98
AC Output	240V AC	Maximum charge rate (A/Ah)	0.4
		Maximum charge current (A)	130
		Maximum discharge current (A)	150

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2.4.3. Converter and Batteries

A converter is an important power electronics device which converts AC to DC or DC to AC. The solar panels will have the output in DC and needs to be converted to AC while providing it to the residents or the grid. The specifications of the Converter used in the simulation is shown in the Table 2. The cost considered for the inverter is 600€/kW with no Operation and Maintenance cost. The lifetime is assumed to be 10 years. This is a bidirectional inverter with three phases. The inverter can be used for solar and other renewable energy sources.

Battery characteristics are specified in Table 2, where Fortress Power eVault LFP-15 were chosen for this research.

3. Results and Discussion

3.1. Scenario 1

In Scenario 1, batteries were considered for storage along with Solar PV and Wind Energy, as renewable sources of energy. The Scenario 1 uses batteries to satisfy the demand when there is dearth in renewable sources production of electrical energy system from Solar PV or Wind Turbine. The components used in Scenario 1 are Peimar SG340P solar panels, Enercon E-48 800kW wind turbines, eVault LFP-15 Battery and Leonics MTP-413F 25kW converter. The cost for batteries is considered as 14000€/Unit. After running the simulations with the input data given from Table 2, the HOMER software runs different scenarios to give an optimized result. According to the simulations, the best scenario was chosen for the analysis. The results of the scenario 1 showed that the NPC will be 95.2M € and a LCOE of 0.786€/kWh. The Figure 12 and Table 3 show the costs associated with this scenario.

The electric load is satisfied with 5331 kW capacity of solar PV, 33,955 kWh of battery capacity and 3200kW of Wind Energy capacity, with 3 wind turbines. The HOMER simulation calculated the annual operating costs as 2.38M €/ year. The Autonomy of the storage in Scenario 1 is 30.2 hours. In Tables 4–6 are the technical specifications of each component under Scenario 1 conditions.

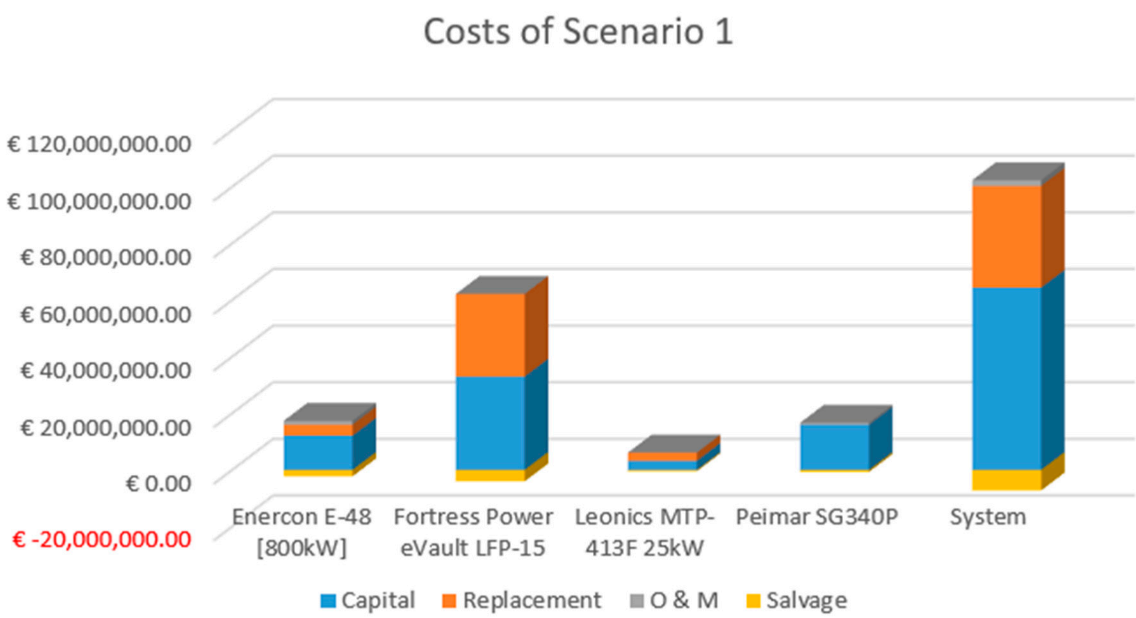

Figure 12. Representation of Capital, Replacement, O & M and Salvage cost values of PV, Wind Turbine, Battery, Converter and the whole system for Scenario 1.

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Table 3. Costs of different components used in Scenario 1.

Component	Capital	Replacement	O & M	Salvage	Total
Enercon E-48 [800kW]	€ 12,160,000.00	€ 3,876,697.38	€ 1,323,777.69	€ -2,184,767.59	€ 15,175,707.48
Fortress Power eVault LFP-15	€ 33,012,000.00	€ 29,164,042.96	€ 0.00	€ -3,954,141.87	€ 58,221,901.08
Leonics MTP-413F 25kW	€ 3,260,278.43	€ 2,880,252.64	€ 0.00	€ -390,512.65	€ 5,750,018.43
Peimar SG340P	€ 15,993,758.47	€ 0.00	€ 689,198.61	€ -638,571.73	€ 16,044,385.35
System	€ 64,426,036.90	€ 35,920,992.98	€ 2,012,976.31	€ -7,167,993.84	€ 95,192,012.34

Table 4. Electrical Specifications of Scenario 1.

Quantity	kWh/yr	Percentage %
Peimar SG340P	8,841,858	48.7
Enercon E-48 [800kW]	9,299,602	51.3
AC Primary Load	9,362,509	100
Excess Electricity	8,540,931	47.1
Unmet Electric Load	7,169	0.0765
Capacity Shortage	9,355	0.0998

Table 5. Technical Specifications of Battery for results of Scenario 1.

Quantity	Value	Units
Batteries	2,358	qty.
String Size	1	batteries
Strings in Parallel	2,358	strings
Bus Voltage	48	V
Autonomy	30.2	hr
Storage Wear Cost	0.236	€/kWh
Nominal Capacity	33,955	kWh
Usable Nominal Capacity	32,257	kWh
Lifetime Throughput	25,136,156	kWh
Expected Life	10	yr
Average Energy Cost	0	€/kWh
Energy In	2,538,404	kWh/yr
Energy Out	2,488,352	kWh/yr
Storage Depletion	724	kWh/yr
Losses	50,775	kWh/yr
Annual Throughput	2,513,616	kWh/yr

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Table 6. Technical specifications of Solar PV and Wind Turbine for results of Scenario 1.

Peimar SG340P.			**Enercon E-48 [800 kW]**		
Quantity	**Value**	**Units**	**Quantity**	**Value**	**Units**
Rated Capacity	5,331	kW	Total Rated Capacity	3,200	kW
Mean Output	1,009	kW	Mean Output	1,062	kW
Mean Output	24,224	kWh/d	Capacity Factor	33.2	%
Capacity Factor	18.9	%	Total Production	9,299,602	kWh/yr
Total Production	8,841,858	kWh/yr	Minimum Output	0	kW
Minimum Output	0	kW	Maximum Output	2,573	kW
Maximum Output	5,410	kW	Wind Penetration	99.3	%
PV Penetration	94.4	%	Hours of Operation	8,339	hrs/yr
Hours of Operation	4,385	hrs/yr	Levelized Cost	0.126	€/kWh
Levelized Cost	0.14	€/kWh			
Clipped production	0	kWh			

3.2. Scenario 2

The Scenario 2 is simulated with solar PV, wind turbines and Pumped Storage Hydropower (PSH). The generic PSH parameters are defined by the reservoir capacity of 1000 m^3 of water to be discharged over a 12-hour time period. The cost for PSH is considered as 2,200€/kW. The HOMER calculates the energy by considering an effective head of 100 m with a turbine generator efficiency of 90%.

The discharge flow rate is calculated by

$$1000\ \mathrm{m}^3 / (12{*}60{*}60) = 0.0231\ \mathrm{m}^3/\mathrm{s} \tag{6}$$

The power generation is calculated using the equation below considering 90% efficiency.

$$9.81 \times 100 \times 0.0231 \times 0.90 \sim\ = 20.44\ \mathrm{kW} \tag{7}$$

$$\mathrm{Energy} = 20.44\ \mathrm{kW} \times 12\ hours = 245.25\ \mathrm{kWh} \tag{8}$$

For the charging cycle of the PSH, the model considers the turbine generator as pump in reverse mode to pump the water back up to the upper reservoir. The flow rate of the pump is calculated and 0.01875 m^3/s is obtained as the pumped flow. The period of time to completely fill the reservoir and electrical energy with pump efficiency of 80% are 14.6 h and 302.7 kWh, respectively. HOMER considers a 22 kW generator. The nominal voltage is 240 V with maximum discharge current of 91.6 A. The capacity of PSH is given by dividing power by the nominal voltage which turns out to be 1059 Ah. The cost for PSH is considered as 2200 €/ kW installed and an operating cost of 4000 €/year.

The Scenario 2 considered the same components of SolarPV and Wind Turbine which are Peimer SG340P and Enercon E-48 with PSH. The Scenario 2 has an NPC of 45.8 M € and an LCOE of 0.379 €/kWh. Figure 13 and Table 7 show the costs of different components of Scenario 2.

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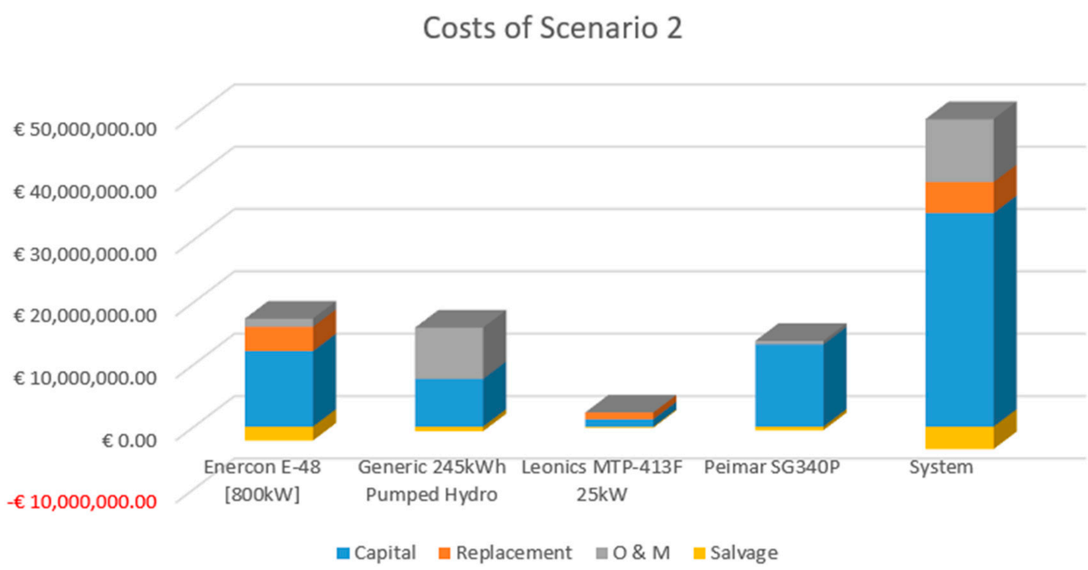

Figure 13. Representation of Capital, Replacement, O & M and Salvage cost values of PV, Wind Turbine, PSH, Converter and the whole system for Scenario 2.

Table 7. Costs of different components used in Scenario 2.

Component	Capital	Replacement	O & M	Salvage	Total
Enercon E-48 [800kW]	€ 12,160,000.00	€ 3,876,697.38	€ 1,323,777.69	€ -2,184,767.59	€ 15,175,707.48
Generic 245kWh Pumped Hydro	€ 7,695,600.00	€ 0.00	€ 8,221,900.52	€ -691,328.02	€ 15,226,172.50
Leonics MTP-413F 25kW	€ 1,220,369.05	€ 1,078,119.94	€ 0.00	€ -146,174.49	€ 2,152,314.50
Peimar SG340P	€ 13,231,667.72	€ 0.00	€ 570,175.36	€ -528,291.65	€ 13,273,551.43
System	€ 34,307,636.77	€ 4,954,817.32	€ 10,115,853.58	€ -3,550,561.75	€ 45,827,745.91

The load being the same as Scenario 1 is satisfied with 4411 kW of solar PV, 3200kW of wind energy capacity and 40,411 kWh of PSH capacity. The autonomy for Scenario 2 is 37.8 hr. Figure 14 shows the percentage of PSH state of charge during different days of the year. In Tables 8–10 are the characteristics of each component obtained for Scenario 2.

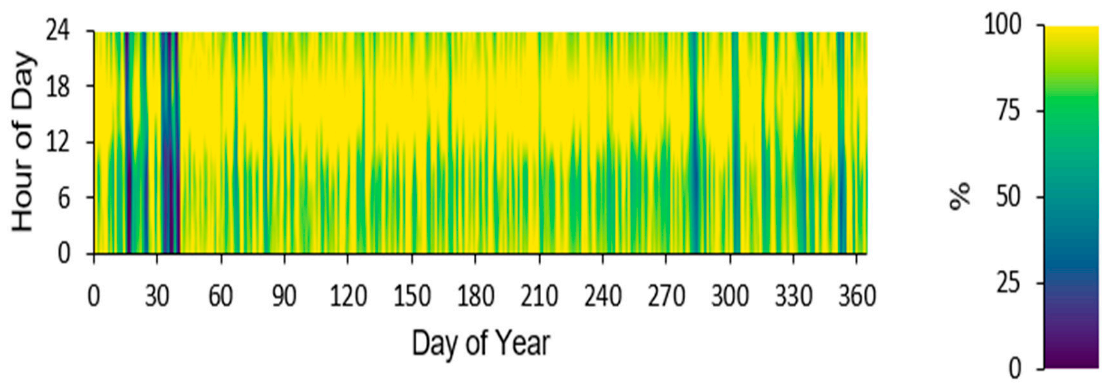

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Figure 14. State of charge of PSH for different hours of the day and different days of the year.

Table 8. Electrical Specifications of Scenario 2.

Quantity	kWh/yr	Percentage %
Peimar SG340P	7,314,886	42.6
Enercon E-48 [800kW]	9,841,470	57.4
AC Primary Load	9,361,602	100
Excess Electricity	7,006,065	40.8
Unmet Electric Load	8,077	0.0862
Capacity Shortage	9,365	0.0999

Table 9. Technical Specifications of PSH for results of Scenario 2.

Quantity	Value	Units
Bus Voltage	240	V
Autonomy	37.8	hr
Storage Wear Cost	0	€/kWh
Nominal Capacity	40,411	kWh
Usable Nominal Capacity	40,411	kWh
Lifetime Throughput	109,828,332	kWh
Expected Life	40	yr
Average Energy Cost	0	€/kWh
Energy In	3,050,767	kWh/yr
Energy Out	2,471,137	kWh/yr
Storage Depletion	18.3	kWh/yr
Losses	579,647	kWh/yr
Annual Throughput	2,745,708	kWh/yr

Table 10. Technical specifications of Solar PV and Wind Turbine for results of Scenario 2.

Solar PV - Peimar SG340P			Wind Turbine - Enercon E-48 [800 kW]		
Quantity	Value	Units	Quantity	Value	Units
Rated Capacity	4,411	kW	Total Rated Capacity	3,200	kW
Mean Output	835	kW	Mean Output	1,123	kW
Mean Output	20,041	kWh/d	Capacity Factor	35.1	%
Capacity Factor	18.9	%	Total Production	9,841,470	kWh/yr
Total Production	7,314,886	kWh/yr	Minimum Output	0	kW
Minimum Output	0	kW	Maximum Output	2,699	kW
Maximum Output	4,476	kW	Wind Penetration	105	%
PV Penetration	78.1	%	Hours of Operation	8,339	hrs/yr
Hours of Operation	4,385	hrs/yr	Levelized Cost	0.119	€/kWh
Levelized Cost	0.14	€/kWh			
Clipped production	0	kWh			

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3.3. Comparison between Scenario 1 and Scenario 2

The HOMER software optimizes with a grid search algorithm to find all the possible solution and then uses the derivative-free algorithm which is owned by HOMER for the least cost system. The Scenarios of load demands with available renewable resources and provides an optimized solution with lowest Net Present Cost (NPC). The optimized result for Scenario 1 has NPC of 95.2M € whereas the Scenario 2, which considered the PSH, has NPC of 45.8M €. Hence, the scenario which used PSH – Scenario 2 had an NPC 51.8% lesser than the one used in Battery – Scenario 1. This can be inferred from the replacement cost of batteries in a long run, since the life of batteries is lesser than the PSH, and the replacement costs will add to the costs in the long run of the projects. Considering the LCOE, in Scenario 1 the LCOE which is 0.786, higher than the Scenario 2 with a LCOE which is 0.379. The LCOE as defined measures the cost of energy showing the economically viable or which is the better project. Since, the HOMER software did not calculate the revenues for both the projects, NPC and LCOE are excellent measuring parameters to compare the economic analysis of the two scenarios.

The capacity for Solar PV in Scenario 2 is 4411 kW which is lesser than the capacity of Scenario 1 which is 5331 kW. The Scenario 2 had more of PSH power being generated with an annual throughput of 2,745,708 kWh/yr where as in Scenario 1 with batteries, the annual throughput is 2,513,616 kWh/yr**.** Due to the high cost of batteries and less lifecycle time, the software had to install more of renewables which is an economic solution than having more storage to satisfy the demand for electricity. Figures 15 and 16 show the state of charge of storage systems in Scenario 2 and 1 and the Solar PV and Wind Turbine satisfying the load demand.

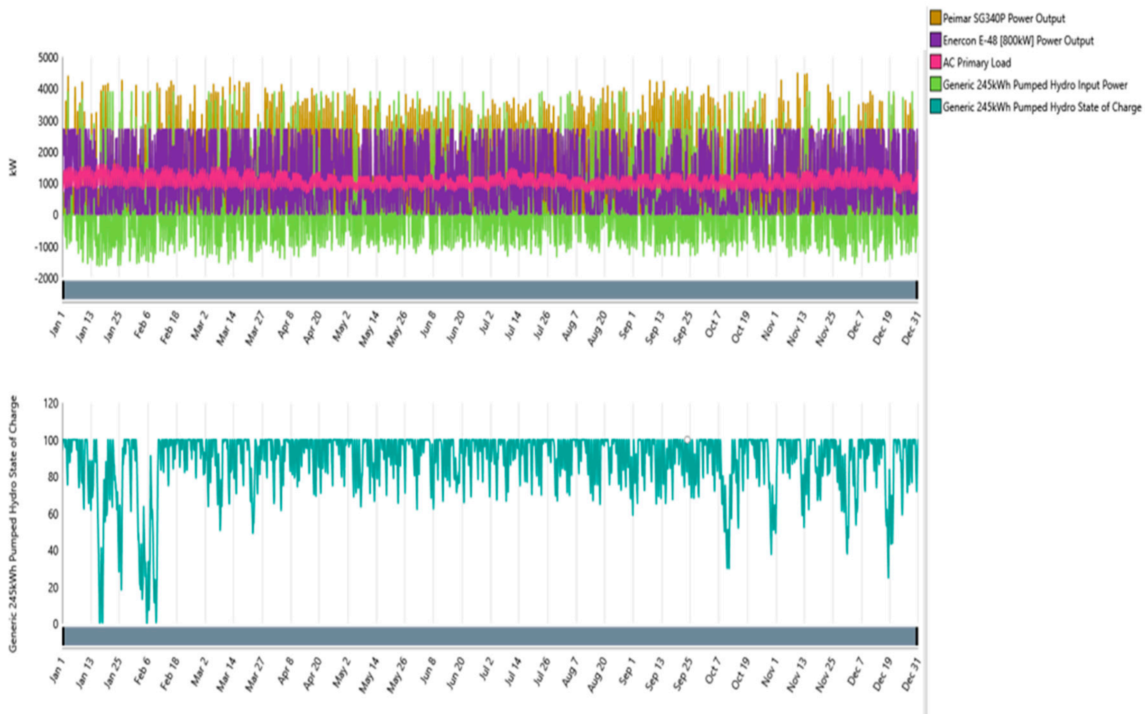

Figure 15. Scenario 2 Solar PV, Wind turbine and PSH power output along with the power demand and PSH state of charge.

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Figure 16. Scenario 1 Solar PV, Wind turbine and Battery power output along with the power demand and Battery state of charge.

3.4. Technical analysis of Scenario 2 with Python

3.4.1. Energy demand and production in different seasons

The hourly results obtained from the modelling for demand and production was exported and used in data analysis of Python. The whole energy demand and production is divided into different seasons which are Winter, Spring, Summer and Autumn. The winter season is divided from start of January to end of February. The spring month is from the start of March until the end of May. The summer season is considered from start of June till the end of August. The autumn is considered from the start of September until the end of December. It can be observed that the solar irradiance is lower in the seasons of winter and autumn which gives a greater role for PSH during day time as well. It is also observed that the load during these seasons is high due to heating. Figures 17–20 show the graphs of power production during the different seasons.

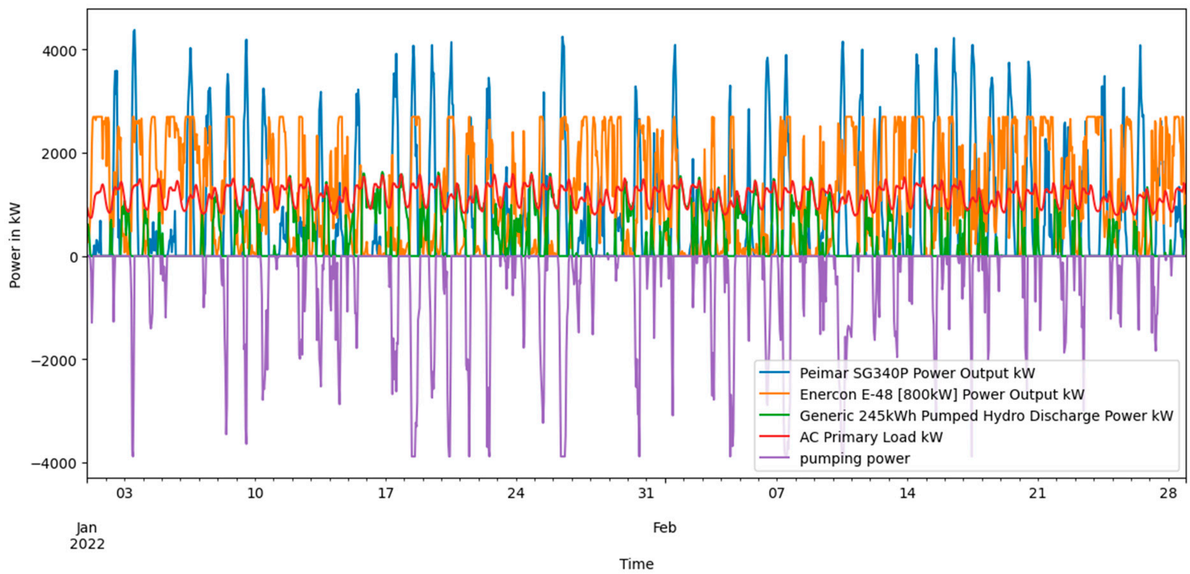

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Figure 17. Power production from Solar PV, Wind Turbine, Pumped storage hydropower charge and discharge power along with the load demand for the season of Winter.

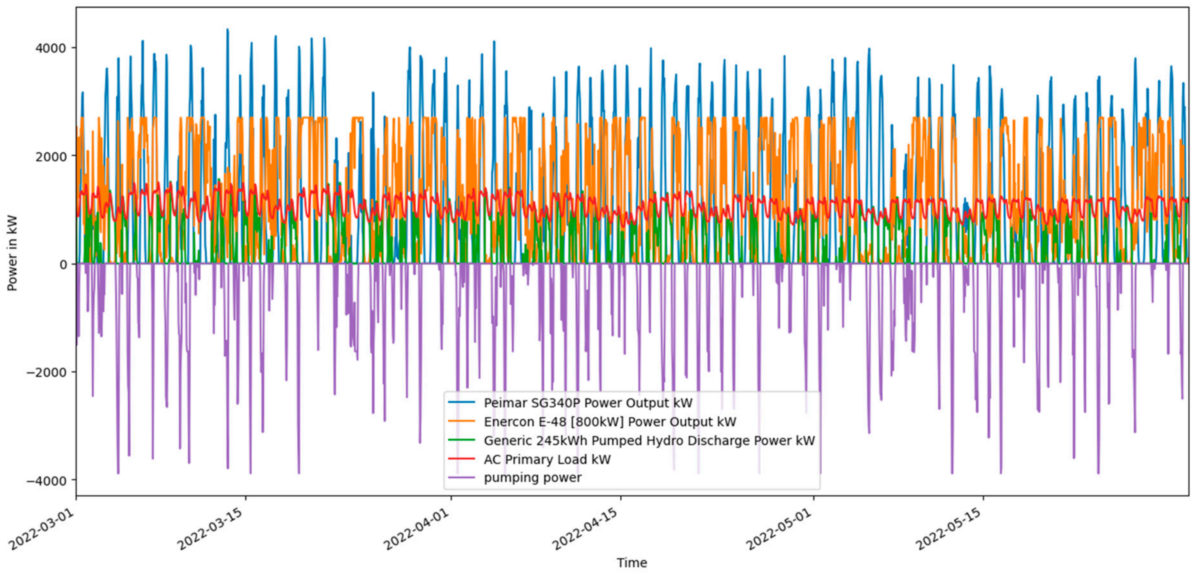

Figure 18. Power production from Solar PV, Wind Turbine, Pumped Storage Hydropower charge and discharge power along with the load demand for the season of Spring.

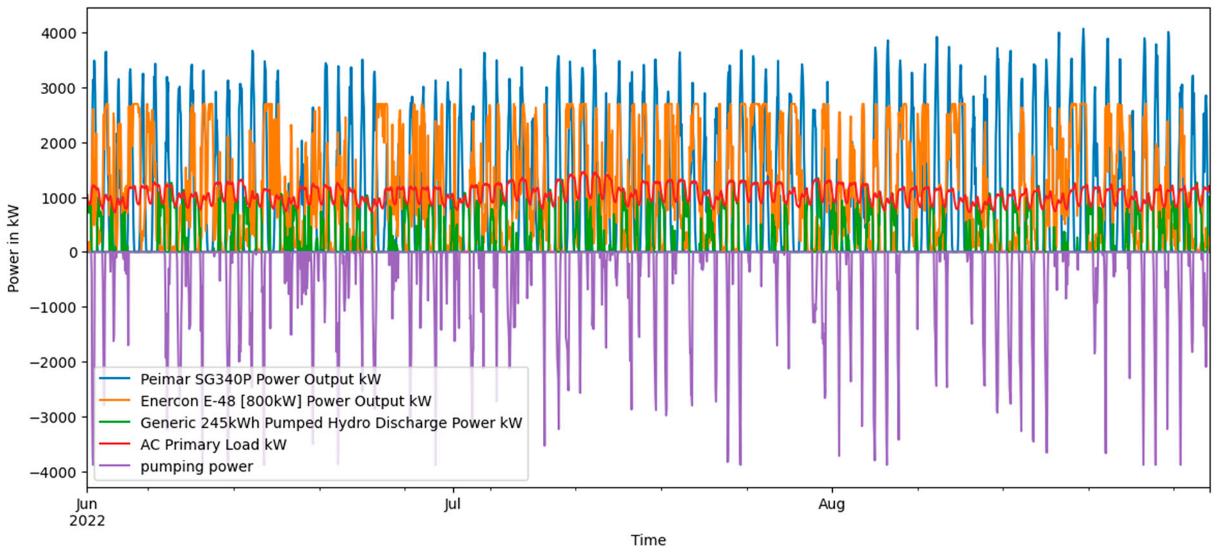

Figure 19. Power production from Solar PV, Wind Turbine, Pumped storage hydropower charge and discharge power along with the load demand for the season of Summer.

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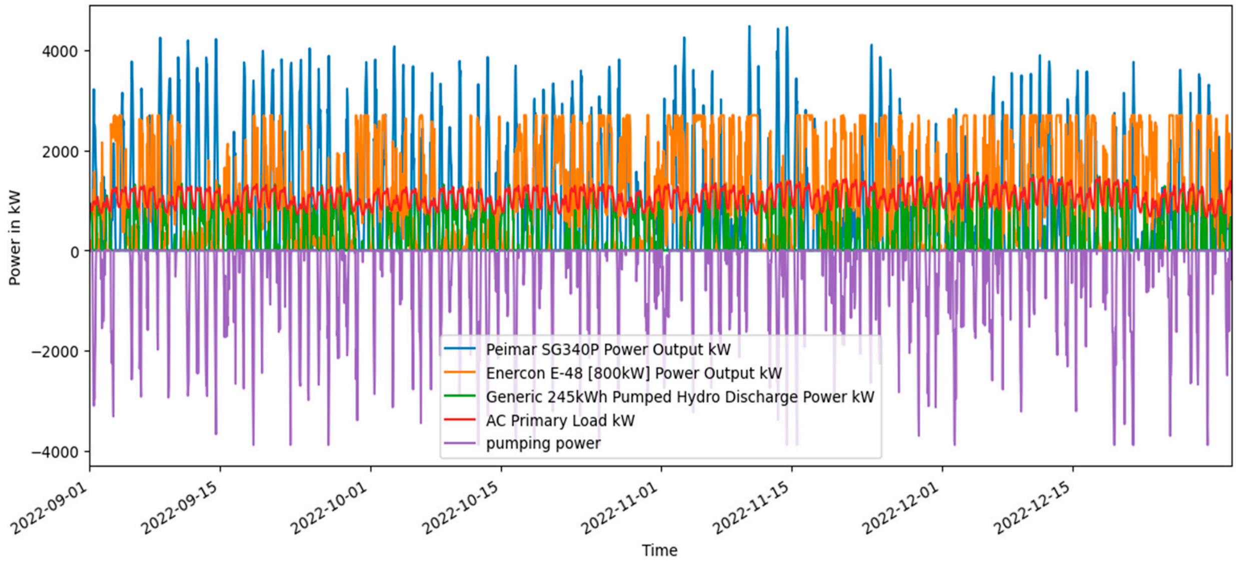

Figure 20. Power production from Solar PV, Wind Turbine, Pumped storage hydropower charge and discharge power along with the load demand for the season of Autumn.

Based on the different seasons analysis, the Pumped Storage Hydropower working conditions will vary. This is mainly due to the highly variable output from the wind energy which depends on the wind speed. Most of the times, the shadow effects on the solar panels also require the need of PSH to keep the demand for power supply. The Figure 21 shows the bar graph of average power production in each month of the analyzed year. Since the solar PV works only during the day for a specific time, while the wind power keeps working for the whole time, the average value of the Wind Power per month is comparable with solar PV.

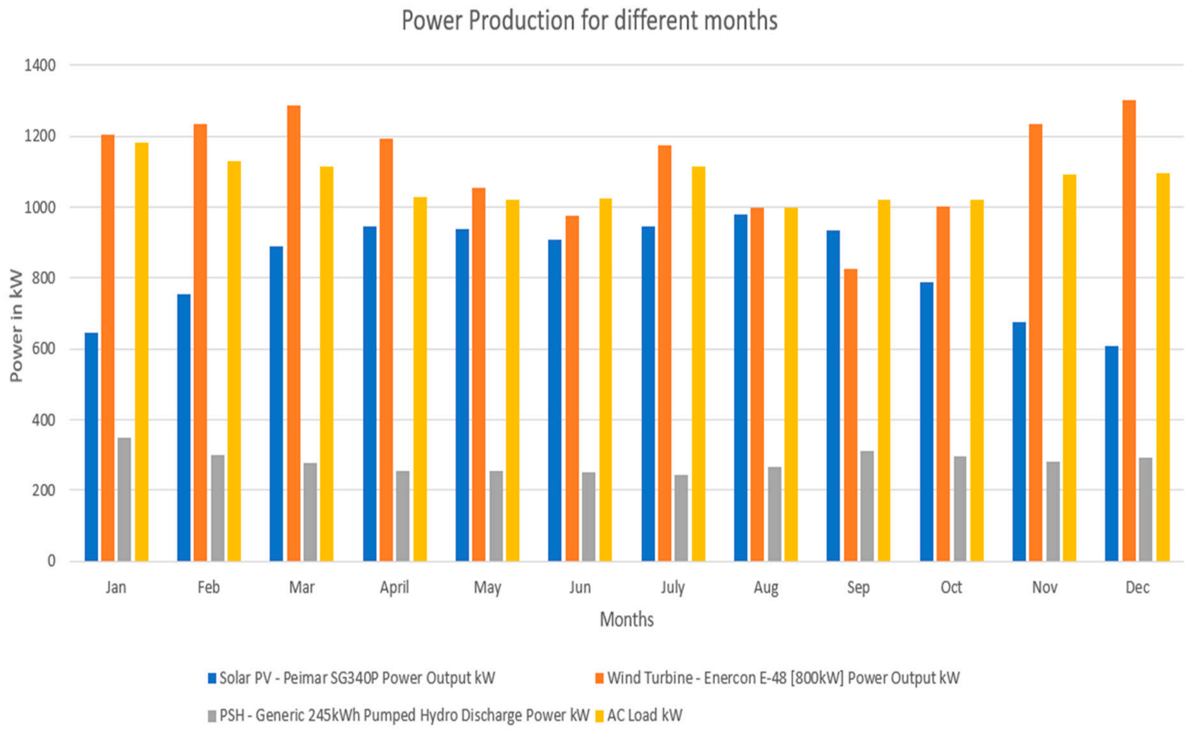

Figure 21. Power production of Solar PV, Wind Turbine and PSH along with load demand of hourly data averaged to months of the analyzed year.

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3.4.2. The need for Energy Storage

To understand the need for energy storage, the graph of power production will give a clear picture on the variability of the power generation by the wind and non-production of solar PV during the night. This can be seen in the Figure 22 where it shows the power production over the 48 hours for two days in January.

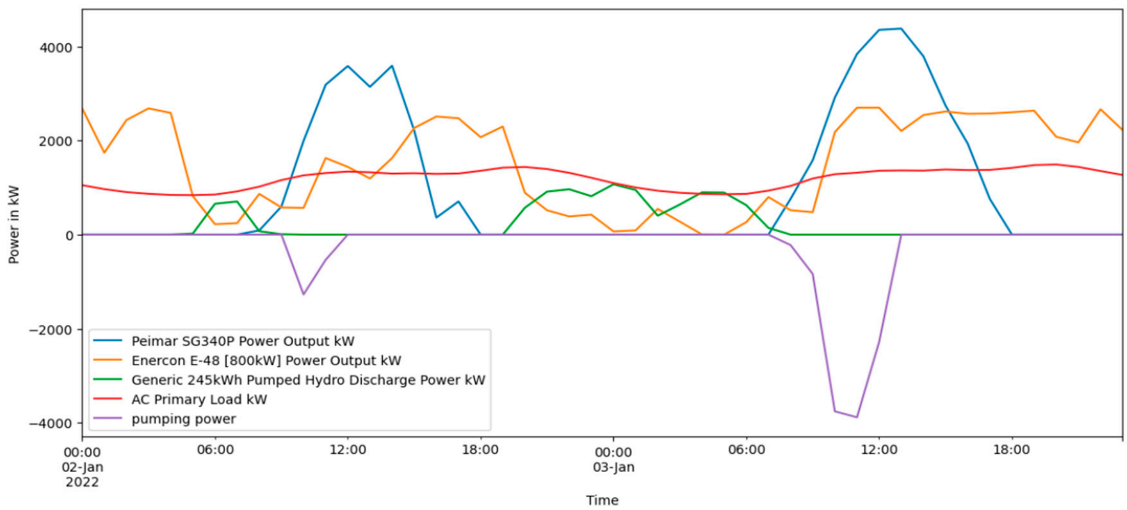

Figure 22. Power production on 2nd-3rd of January 2022 with solar PV, wind turbine, PSH charge and discharge power along with the demand for power.

It is noticed that to keep the demand satisfied, whenever there is a dearth of power from solar and wind turbine, the PSH satisfies the demand for the power. It is also recognized that whenever there is an excessive power production from solar PV usually during the day time, the PSH is being pumped to recharge the storage. The pumping of water to the upper reservoir ensures that PSH can be used again during the need of the demand for power. This can be clearly visualized with profile graphs as well as the variability of wind power can also be realized. Figures 23–25 show the profile of solar PV, wind turbine power output and PSH input power.

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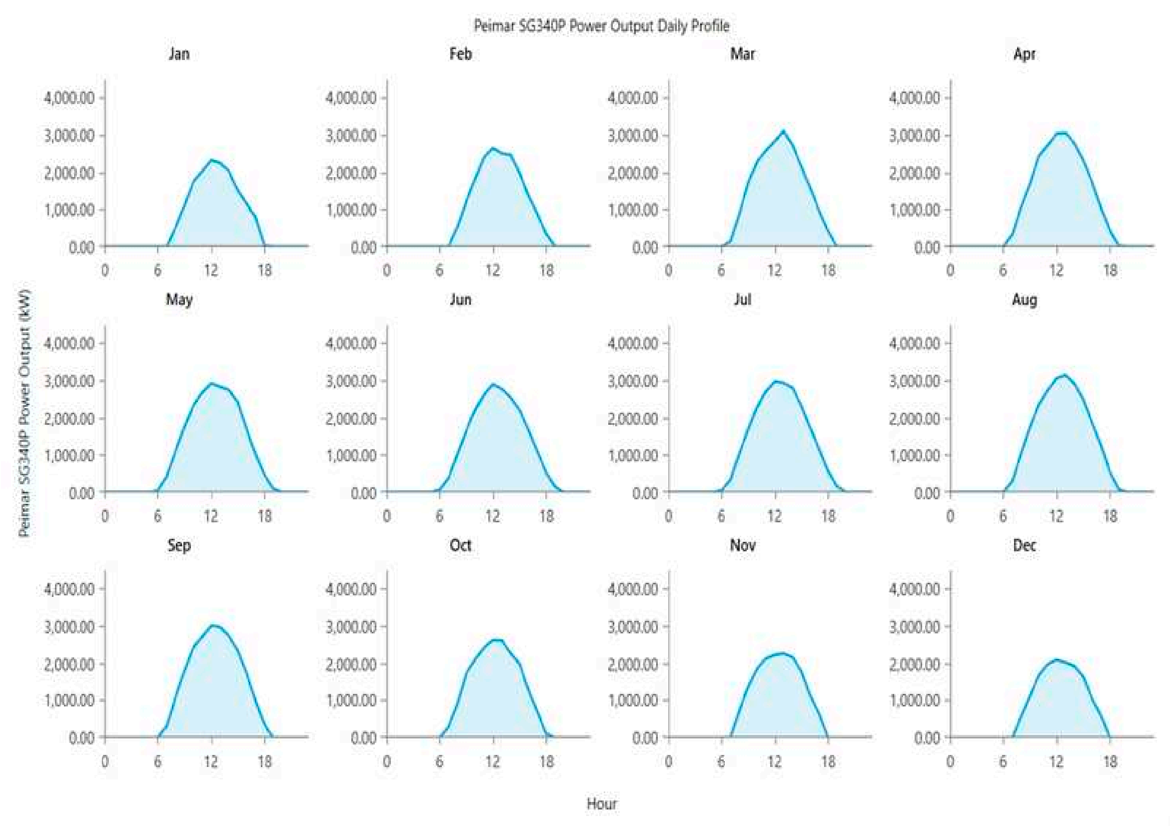

Figure 23. Average daily profile of solar PV output for different months of the year 2022.

It can be noticed that the production of power from solar PV is low with a peak close to 2000 kW during the winter seasons. The production of electricity also can be seen only during the day time approximately from 7 a.m to 6 p.m. There is also a gradual increase and decrease in power production over time which leaves the demand for power vulnerable and needs to be satisfied with wind power and PSH. The variability of wind power can be seen in the profile of wind output of Figure 24.

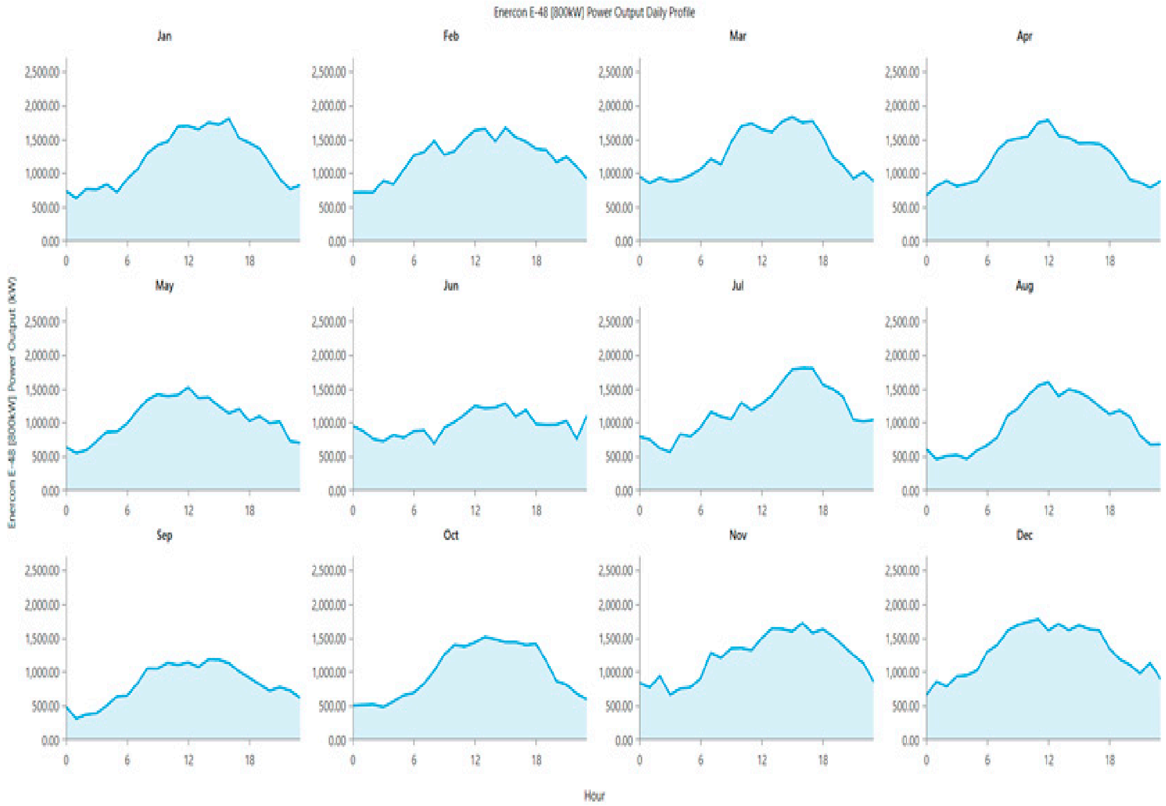

Figure 24. Average daily profile of wind turbine Enercon E-48 output for different months of the year 2022 which shows the variability of power generation.

The variability of the power production in wind turbine is attributed to the continuous variability in the wind speed. Due to this variability, the profile of the PSH has power being produced at night where the power from solar PV is not available.

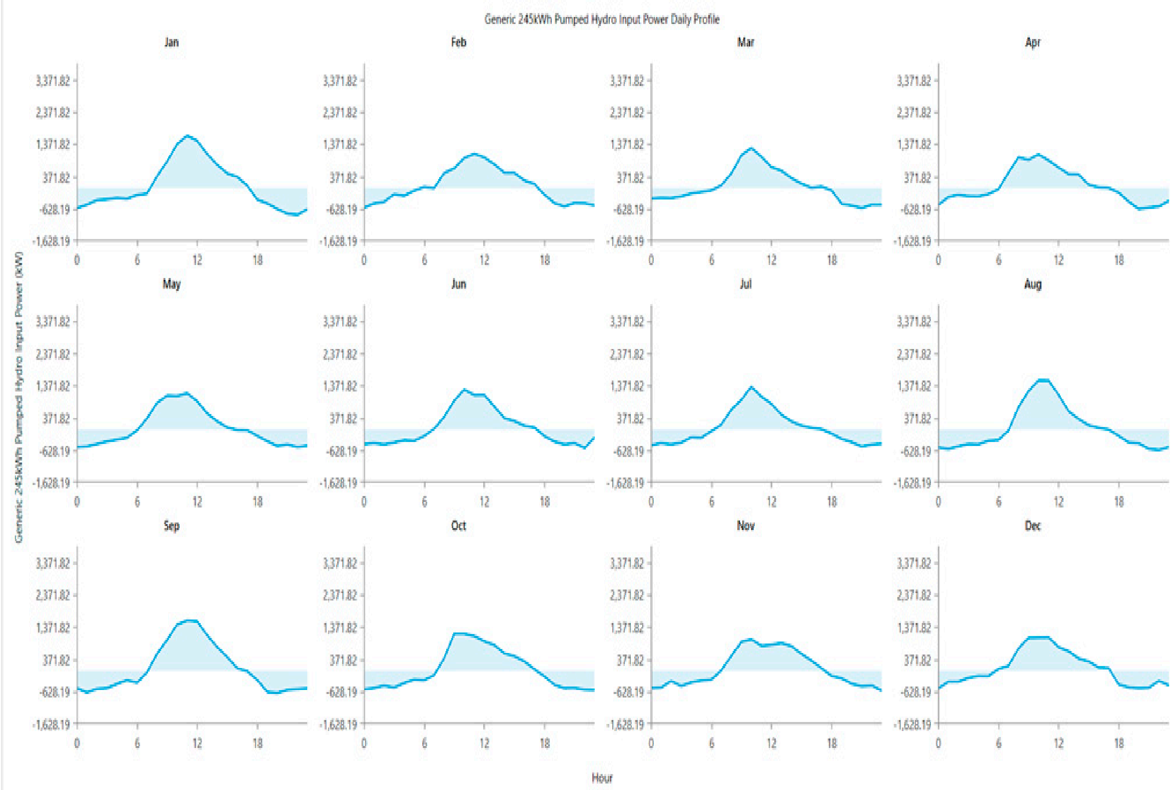

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Figure 25. Average daily profile of PSH input and output power for different months of the year 2022.

The Figure 25 clearly indicates that the input power for PSH is during the day time where the production of power is from solar PV and it is seen that during the autumn and winter months there is more usage of power from PSH as the power from solar PV reduces and PSH will have to compensate the variable power produced from wind turbine.

3.5. Sensitivity Analysis

Sensitivity analysis was performed with Scenario 2, as it was the optimal solution. The sensitivity analysis can be performed with HOMER software where variable values for different parameters can be given. The scenario considering the 100% state of charge for PSH, the capital cost of SG-340P Solar PV and Enercon E-48 was varied as shown in the Table 11**.**

Table 11. Capital cost multiplier for Sensitivity analysis.

SG 340P solar PV	Enercon E-48 wind turbine
0.2	0.2
0.8	0.8
1	1
2	2
3	3
4	4

Figure 26 shows the sensitivity graph. The capital cost was considered with the variation of both less than and greater than the unit multiplier. The main reason for this consideration is that there have been a lot investments happening in renewable energy projects and also the effect of war which is resulting in inflations. The graph covers the variation of Solar PV SG 340P and Enercon E-48 Wind Turbine for the range of values from 0.2 to 4 in their capital cost multiplier. The various area shows the coverage of the NPC for an optimum solution. The sensitivity analysis covers the different scenarios of different considerations in calculation for microgrids. 36 NPC values are represented in the Figure 26 which also shows the area representation for different cases over the given capital cost multiplier range. It is important to have the scenarios or projects in simulation as close as possible to the expected reality.

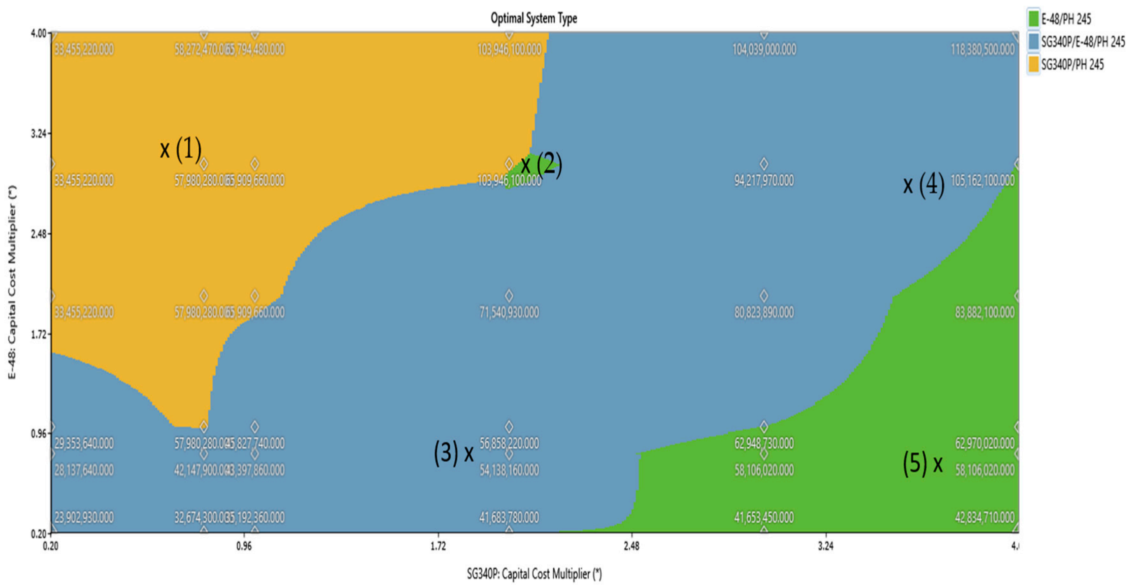

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Figure 26. Sensitivity analysis superimposed with total net present cost for cost multipliers of Solar PV and Wind Turbine.

The region of orange is the area having Solar PV and PSH as a feasible option with the economics and the blue region suggests having a combination of Solar PV, Wind Turbine and PSH. The green region represents the region where Wind Turbine based model dominates. These regions in the graph can be attributed with the capital cost multipliers used. The region with low Wind Turbine capital cost multiplier but higher Solar PV capital cost multiplier results in the Wind Turbine based Microgrid model and vice versa. The green region at approximately Solar PV capital cost multiplier from 1.9 to 2.2 and Wind Turbine capital cost multiplier from 2.8 to 3.10 results in a Wind Turbine based model with PSH due to the lower NPC compared to other models. The sensitivity graph can be visualized by choosing specific points (1,2,3,4,5) as shown in the Figure 26 and observing the different models that are possible as shown in Figure 27 a) to e).

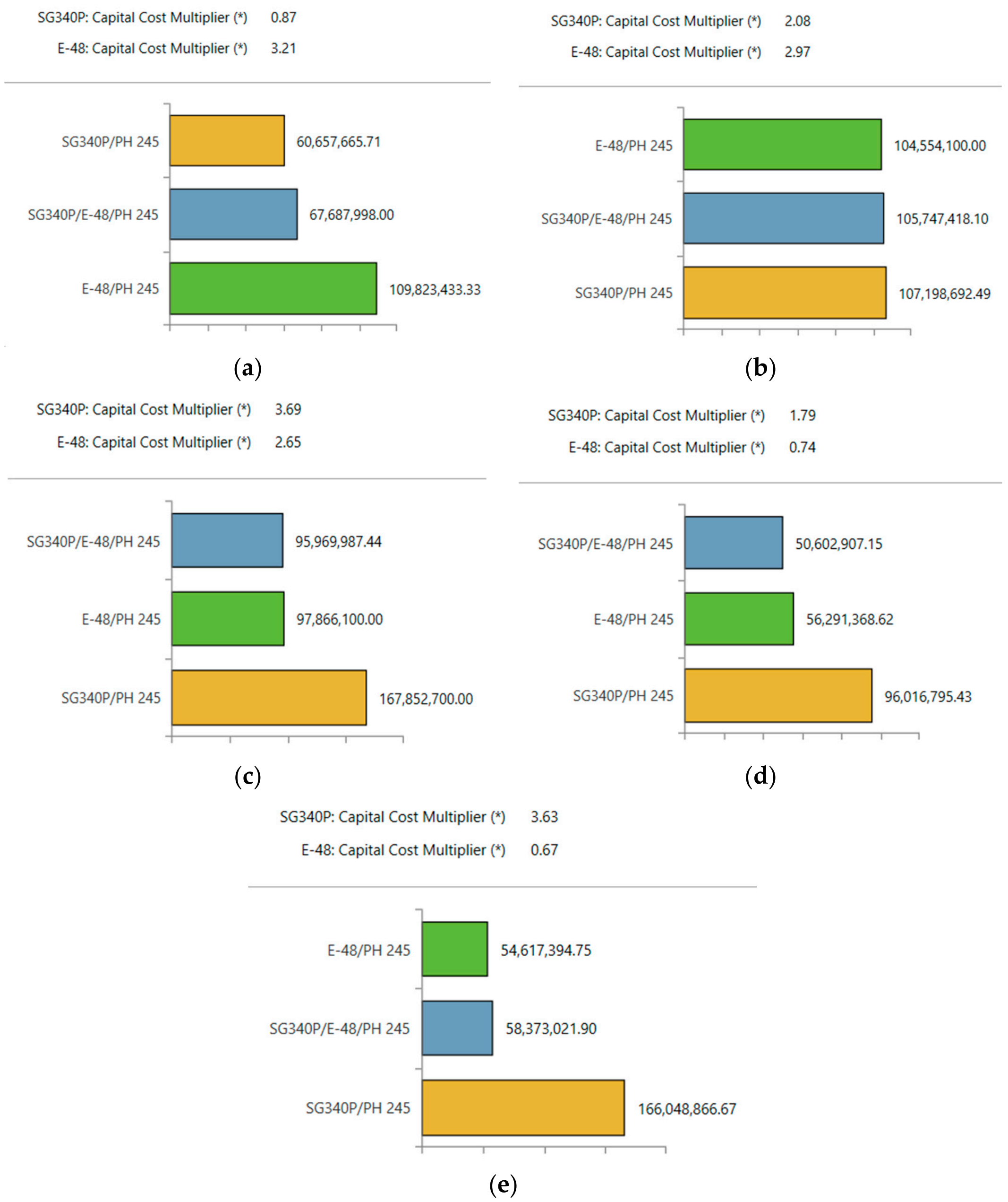

Figure 27. Interpolated values of capital cost multipliers for Solar PV and Wind Turbine in the developed sensitivity analysis at: a) point 1; b) point 2; c) point 3; d) point 4; e) point 5.

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4. Conclusions

In an ever-increasing demand for energy in the foregoing world, due to climate change and global warming issues, the need for energy transition has become critical. The rise in Solar PV and Wind Energy renewables have given rise to potential problems for variability in power production. The storage of energy is necessary for the problem of intermittent power production from renewables. Batteries and Pumped Storage Hydropower are some of the storage technologies that are being used.

This research discussed the analysis of two scenarios using HOMER and Phyton softwares. The HOMER model finds an economic solution for the microgrid which satisfies the demand of the load. Scenario 1 used batteries as storage with solar PV and wind turbine as renewable sources of power generation. An inverter is used to convert DC to AC. Scenario 2 used PSH with the same renewable sources as Scenario 1 and from same manufacturers. The simulations resulted in a NPC of 95.2 M € and a LCOE of 0.786 €/kWh for Scenario 1, whereas Scenario 2 resulted in a NPC of 45.8 M€ and a LCOE of 0.379 €/kWh, clearly indicating that Scenario 2 with PSH is the most economical solution. The real projects should be chosen based on the location and the batteries have a small lifetime in comparison with PSH which result in replacement costs. Even though the cost of batteries is getting reduced over time, it is still difficult to compete with PSH economically. The technical analysis of Scenario 2 indicates the need for the storage of the data obtained from the HOMER. Data analysis with Python is done to separate data into different seasons and was plotted to understand the role of PSH in winter and autumn seasons where the power from PV is less. Sensitivity analysis gives an advantage to analyzing projects by varying important variables. The most optimal solutions with different capital cost multipliers for Solar PV - SG-340P and Wind Turbine - Enercon E-48 resulted from the combination of Solar PV, Wind Turbine, and PSH.

The topic further has scope with machine learning techniques to forecast energy demand and weather data. Modern digital technologies are used to develop smart solutions and smart grids with the Internet of Things (IoT) where the lowest cost of energy is inserted into the grid automatically and the PSH started based on the power demand and weather forecast conditions.

The other advantages that are worth mentioning of hydropower as a storage solution against batteries are that i) Hydropower is a huge "water battery" where the size between battery and hydropower, the flexibility, renewable energies integration can be made in a complementary way allowing to better face to climate changes and local climate weather harmonization, fighting against water scarcity, social and environmental impacts creating a water reserve to fight fires and for drinking and irrigation water uses. ii) Hydropower multi-purposes hybrid water-energy solution is more and more of utmost importance in near future. iii) The lifetime of PSH is comparably higher than Batteries, guaranteeing a long-life solution. iv) The number of cycles of charging and discharging can be high for PSH without losing the lifespan of the system, when compared with batteries. These advantages and the economic analysis suggest that PSH can be a better solution as storage for microgrid and off-grid systems in comparison with batteries. However, with the trends for future solid batteries maybe in the future, a solution will incorporate both components, but PSH presents always more technical, environmental and social benefits for the population welfare.

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