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Techno-Economic Optimization of Stand-Alone Hybrid Renewable Energy Systems

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Abstract

Today, all nations aim to reach 100% renewable energy use by 2050 and to completely end their dependence on fossil fuels. One of the crucial steps to achieve this goal is the effective use of solar-wind-based hybrid energy systems. However, energy storage solutions are needed to increase the continuity of the systems. This study aims to evaluate the techno-economic and environmental suitability of a solar-wind-based hybrid energy system to meet the electricity demand of a residential area in Izmir. As a result of the analyses carried out within the scope of the study, it was concluded that the installed power distribution of the hybrid energy system is the most economical and feasible with 96.7 kW of solar energy and 12 kW of wind energy. With this approach, it was concluded that it is possible to meet the entire demand from renewable energy sources and that it is compatible with the 2050 targets. However, the high system investment costs make it economically feasible only in regions with high potential.

Keywords: *Renewable energy, Hybrid systems, HOMER, Optimization, Storage*

Makale Bilgisi

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Bağımsız Hibrit Yenilenebilir Enerji Sistemlerinin Tekno-Ekonomik Optimizasyonu

Özet

Günümüzde tüm uluslar, 2050 yılına kadar %100 yenilenebilir enerji kullanımına ulaşmayı ve fosil yakıtlara olan bağımlılıklarını tamamen bitirmeyi hedeflemektedir. Bu hedefe ulaşabilmenin önemli adımlarından biri de güneş-rüzgâr tabanlı hibrit enerji sistemlerinin etkin kullanımı olarak ön plana çıkmaktadır. Ancak sistemlerin sürekliliklerini artırmak amacıyla enerji depolama çözümlerine ihtiyaç duyulmaktadır. Bu çalışma, İzmir'de bir yerleşim yerinin elektrik ihtiyacını güneş-rüzgâr tabanlı hibrit enerji sistemiyle karşılanması için tekno-ekonomik ve çevresel uygunluğunu değerlendirmeyi amaçlamaktadır. Çalışma kapsamında gerçekleştirilen analizler sonucunda, hibrit enerji sisteminin kurulu güç dağılımının, 96,7 kW güneş enerjisi ve 12 kW rüzgâr enerjisi olacak şekilde en ekonomik ve uygulanabilir olduğu görüşüne varılmıştır. Bu yaklaşım ile talebin tamamının yenilenebilir enerji kaynaklarından karşılanmasının mümkün olduğu ve 2050 yılı hedefleriyle uyumlu olduğu kanaatine varılmıştır. Ancak sistem yatırım maliyetlerinin yüksek olması, yalnızca potansiyeli yüksek bölgelerde ekonomik olarak uygulanabilirliğini ortaya koymaktadır.

Anahtar Kelimeler: *Yenilenebilir enerji, Hibrit sistemler, HOMER, Optimizasyon, Depolama*

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1 Introduction

In today's world, energy plays one of the most important roles in a country's development. It is a crucial part of the country's welfare, growth, and economy. Fossil fuels like coal, oil, and natural gas have been crucial energy sources for industrial, agricultural, residential, and commercial uses since the Industrial Revolution. [1].

However, due to their environmental damage and limited nature, their usage has been restricted; moreover, climate change and environmental pollution resulting from the burning of fossil fuels are among the greatest challenges facing humanity [2].

Renewable energy holds significant potential to meet the increasing energy demands. Particularly over the past fifty years, oil crises have driven researchers to conduct numerous studies to enhance the efficiency of renewable energy sources with new technologies [3].

Wind and photovoltaic (PV) solar power are popular and commonly utilized energy sources worldwide. However, relying solely on wind and PV solar energy is not entirely dependable, consistent, or available at all times due to factors like climate change, seasonal variations, day-night cycles, precipitation, solar radiation, and fluctuations in wind speed. [4].

During the daytime, when solar radiation is more effective, the PV system will generate electricity. However, at night, when there is no solar radiation, if there is sufficient wind speed, the wind turbine system will generate energy to meet the load demand [5].

In this hybrid system, PV solar energy can make up for the absence of wind energy, helping to stabilize energy output and mitigate fluctuations to improve grid stability. [6].

Therefore, there are many positive outcomes of using renewable energy sources in a hybrid energy system. Renewable hybrid energy systems can be established at high capacities and provide energy storage even in conditions where energy cannot be generated, or the grid is not accessible [7].

This paper presents a new methodology for the optimization of hybrid renewable energy systems, providing an approach that balances technical performance with economic viability. At the same time, it analyses cost-effective solutions for off-grid hybrid systems and offers sustainable energy solutions, especially for rural areas.

2 Objective and methodology

In this section, regional data on the hybrid energy system has been analysed. A settlement consisting of 42 independent residences has been examined, with the population in the settlement ranging from 105 to 130 people. Additionally, the distance from the settlement to the Bornova-Izmir district is 13,7 kilometres. The 2022 electricity consumption data for the region was obtained from the settlement management and is shown in Table 1.

The total electricity consumption for the year 2022 was recorded as 74.298,02 kWh.

An analysis of consumption habits reveals that consumption during the summer months is approximately twice as high as in the spring and autumn months. In addition to electricity consumption, the load profile should also be modelled.

The region's electricity consumption was centrally associated with a single meter and measured by distributing it to buildings through sub-meters.

Therefore, hourly or daily load data at the building scale are not available. In this context, considering similar studies in the literature for daily consumption habits, a sample load profile was selected in HOMER, and the entered values were sized using HOMER. The resulting data are shown in Figures 1 and 2.

Table 1: Monthly consumption data for the settlement area

Months	January	February	March	April	May	June
Consumption (kWh)	3.686,54	3.450,23	4.490,02	5.860,66	6.711,40	7.940,25
Total Share	5%	5%	6%	7%	9%	11%
Months	July	August	September	October	November	December
Consumption (kWh)	9.452,67	8.885,81	8.223,83	6.049,71	5.388,02	4.159,18
Total Share	13%	12%	11%	8%	7%	6%
Total Consumption and Share			74.298,02 kWh		100%	

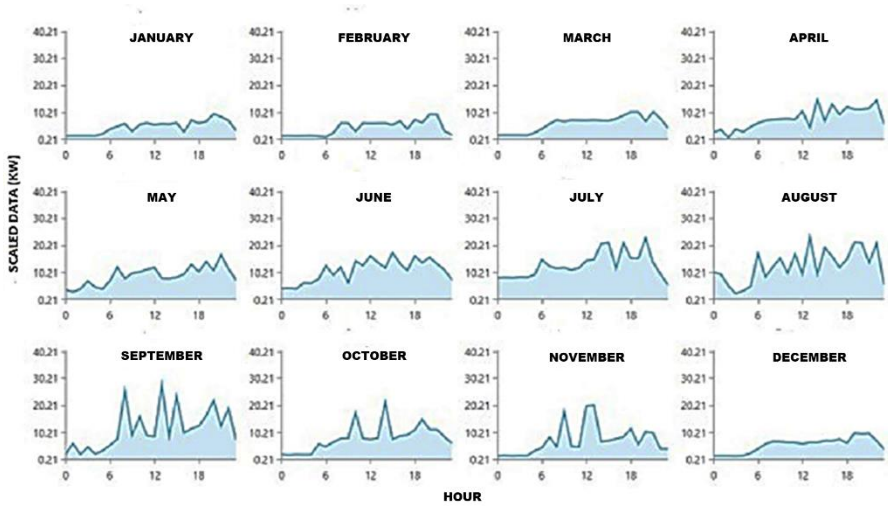

Figure 1. Hourly load profile by month for the settlement area

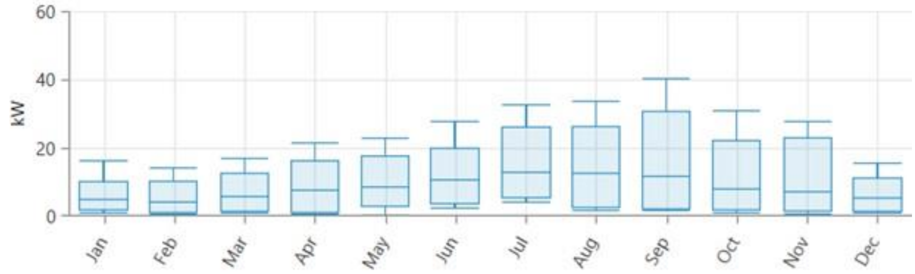

Figure 2. Daily load profile for the settlement area

2.1 *Wind energy potential*

The meteorological data used by the HOMER program are based on NASA data. Figure 3 below shows the average wind speed graph for the settlement. One of the most important parameters in determining the wind energy potential, which will form the hybrid system together with solar energy, is the average wind speed.

2.2 *Solar energy potential*

HOMER utilizes Global Horizontal Irradiance (GHI) and the Clearness Index to determine the output of photovoltaic modules. GHI indicates the total solar irradiation received on a horizontal surface, while the Clearness Index assesses atmospheric clarity. This index quantifies the fraction of solar radiation that successfully passes through the atmosphere and reaches the Earth's surface. It is a dimensionless number expressing the ratio of surface radiation to extra-terrestrial radiation, and it ranges from 0 to 1. The Clearness Index is high in clear and sunny weather, while it is lower in cloudy conditions. In this study, it was decided to use NASA database-based data for HOMER’s database. Accordingly, the global horizontal irradiance and clearness index graphs for the region are provided in Figure 4 below.

Figure 3. Average wind speed by month for the settlement area

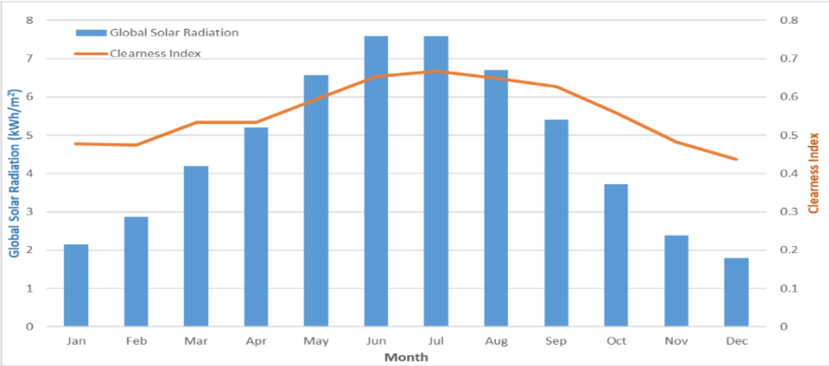

Figure 4. Daily average horizontal irradiance and clearness index by months for the settlement area

2.3 *HOMER Software*

The Hybrid Optimization Model for Electric Renewables (HOMER) is widely recognized as a popular, user-friendly software that is free during its trial period. It is well-suited for quickly conducting preliminary feasibility studies, optimization, and sensitivity analysis of various system configurations. This program was developed and made available by NREL (National Renewable Energy Laboratory) in 1993 for both grid-tied and standalone systems, HOMER has since been utilized by over 250,000 users across more than 190 countries [8].

Power output interruptions, seasonal variations, and the inability to consistently meet instantaneous load demands in renewable energy systems can result in increased system complexity. The HOMER software is specifically developed to address these challenges. It simulates and optimizes both grid-connected and standalone renewable energy systems, incorporating various combinations of photovoltaic arrays, wind turbines, hydropower, biomass, internal combustion engine generators, microturbines, fuel cells, batteries, and hydrogen storage.

Figure 5 represents the conceptual analysis method of the HOMER programme. In the conceptual analysis approach, the nested circles indicate that the sub-functions have multiple steps. In other words, it is stated that there is more than one optimisation step in the sensitivity analysis and each optimisation step has more than one simulation.[9].

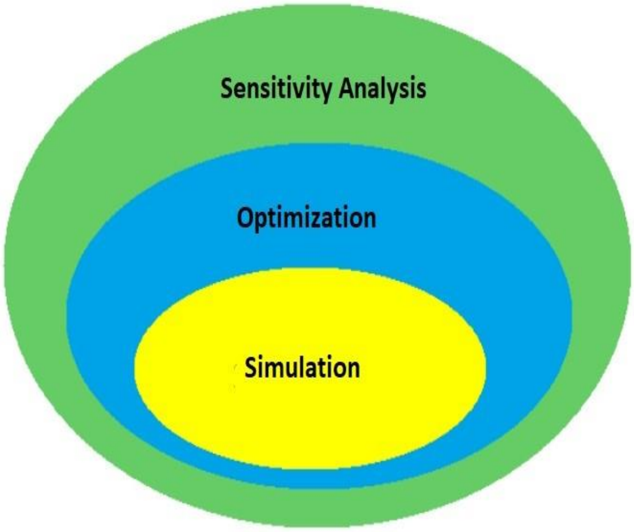

Figure 5. HOMER's conceptual analysis method

3 System components

HOMER software is one of the most widely used simulation tools for system design and optimisation [10].

This software facilitates performing preliminary feasibility tests for various system configurations of different sizes and conducting configuration and sensitivity analyses for desired energy systems.

When designing a system using HOMER, loads, energy sources, and system components are considered and analysed. For accurate simulation results, these data must be entered into the program without errors.

The primary components of the system consist of photovoltaic (PV) solar panels, a wind turbine, a battery, and a converter. The PV solar system and wind turbine work together to meet the load demand. Since the system is off-grid, excess energy is stored using an energy storage system. The system components are examined in the subsections.

3.1 Wind turbine

The Bergey Excel 6 kW turbines were chosen for this analysis for two main reasons [11]. Firstly, these turbines do not have a very high capacity. This situation provides good opportunities for optimizing the number of turbines. (A low capacity per turbine allows the software to better adjust to the optimum wind capacity.) The parameters of the Bergey Excel 6 turbine are shown in Table 2.

This turbine has been specifically developed for microgrid applications. Currently, turbine capacities used in large wind power plants can go up to 16 MW, but using such a large turbine in settlement areas may not be practical.

In the HOMER algorithm, the lower the system capacity, the higher the resolution. Therefore, a low turbine power is preferred.

In summary, when determining the system power, instead of having power change steps in the MW range, considering change steps of 6 kW will allow the result of the optimisation process to be closer to the optimum capacity of the wind turbine.

In distributed energy systems, constructing the system in a modular way provides advantages in case of any failure. Therefore, a smaller-power wind turbine has been chosen.

The wind turbine used in the simulation has a capacity of 6 kW, an initial investment cost of $7.650, a replacement cost of $7.650, and an annual operation and maintenance cost of $480.

Table 2. Parameters of the wind turbine [10]

Model	Bergey Excel 6
Capacity	6 kW
Initial Investment Cost	$7.650
Replacement Cost	$7.650
Operation and Maintenance Cost	$480/year

3.2 PV Module

HOMER software offers a variety of PV modules defined in its library. In this study, the chosen module is not available in the HOMER library and has been added externally based on its brochure specifications.

The module used in this study is the Sirius brand ELNSM72MHC-HV Series 144-cell MONOPERC photovoltaic module [12].

The total losses in the study are assessed as 15,2%. The PV solar module used in the simulation has a capacity of 545 W, an initial investment cost of $540, a replacement cost of $540, and an annual operation and maintenance cost of $2/kWp.

Table 3. Electrical data for the PV solar panel [12]

Parameter	Value
STC Maximum Power	545 Pmp
Open-Circuit Voltage	49,75 Voc
Short-Circuit Current	13,93 Isc
Maximum Power Voltage	41,8 Vmp
Maximum Power Current	13.04 Imp
STC Module Efficiency	21,1 %
Power Tolerance	+4,99 W
Maximum System Voltage	1500 V DC
Maximum Series Fuse Rating	25 A

3.3 Batteries

Batteries store electricity in chemical form and can be recharged and reused to ensure continuous operation when needed. To prolong the lifespan of a battery, it is crucial to maintain the battery charge within 20% [13, 14].

Table 4. Specifications of the selected battery

Parameter	Value
Nominal Capacity	1 kWh
Nominal Capacity (Ah)	167 Ah
Charge-Discharge Efficiency	90%
Maximum Charge Current	167 A
Maximum Discharge Current	500 A
Minimum State of Charge	20%
Lifetime	15 years
Initial Investment Cost	$550
Replacement Cost	$550
Operation and Maintenance Cost	$20/year

The specifications of the battery technology used in this study are presented in Table 4. To enhance optimization accuracy, a 1 kWh capacity battery has been used. This allows for the gradual differentiation of each increase. The battery used in the simulation has a capacity of 1 kWh, an initial investment cost of $550, a replacement cost of $550, and an annual operation and maintenance cost of $20.

3.4 Inverters

An inverter enables the transfer of energy between direct current (DC) and alternating current (AC), functioning similarly to a rectifier. It converts the DC power generated by the photovoltaic module and battery output into AC. When there is an excess of wind energy generation, a rectifier changes the AC power back into DC for storage in the battery system. The power rating of inverters can be calculated using Equation 1. [15-20].

$$P_{inv} = \frac{P_{peak}}{\eta_{inv}} \quad (1)$$

The converter used in the simulation has an initial investment cost of $530, a replacement cost of $530, and an annual operation and maintenance cost of $0. The specifications of the selected converter are shown in Table 5.

Table 5. Specifications of the selected inverter

Parameter	Value
Inverter Efficiency	95,8%
Rectifier Efficiency	95,8%
Initial Investment Cost	$530
Replacement Cost	$530
Operation and Maintenance Cost	$0/year
Inverter Lifespan	10 years

4 Results and discussion

The operating scenario of the hybrid energy system is illustrated in Figure 6.

As seen in this scenario, the PV system is connected to the DC bus of the storage system, while the electrical loads and wind turbine are connected to the AC bus. The transfer between these systems is managed through the converter connected to both the DC and AC buses. Below is a table showing the results of simulations for the relevant hybrid system configurations conducted in the HOMER software.

As a result of the simulations, it has been determined that System 1 is the optimal system. The presented model has achieved the three main objectives of this study: First, to evaluate the feasibility of hybrid photovoltaic (PV) solar/wind energy systems in residential areas; second, to examine the feasibility of using only wind energy; and finally, to compare and analyze systems that use only PV solar energy. However, some factors were not considered in this model. HOMER assumes wind energy production to be uniform based on the average wind speed for each month, thereby neglecting fluctuations in the produced wind energy. Due to the challenge of instant matching of current power supply and demand, fluctuations in wind power also pose a significant issue for grid integration of these systems. This is one of the reasons highlighting the importance of combined solar and wind energy systems that cannot be represented by the simulation model of this project.

From an economic perspective, if the project includes a grid and electricity sales are made to the grid, regular income from grid electricity sales could help recover project capital and particularly operating expenses, making the project more economical compared to grid-independent systems. Finally, hybrid energy systems aim to provide power reliability to rural and remote communities, thereby promoting sustainable development. Power reliability is essential not only for the success and improvement of small businesses and livelihoods but also for educational purposes. The implementation of hybrid energy systems brings development opportunities to these areas, making their applications socially sustainable.

This study has addressed sustainability in all its aspects. Environmentally, the research aims to reduce greenhouse gas emissions from power plants worldwide particularly in Turkey by promoting the use of renewable energy sources. It could also increase the application of grid-independent systems for rural electrification. However, the presented model does not account for the environmental impacts over the lifecycle of hybrid projects. For example, greenhouse gas emissions and resource consumption resulting from the manufacturing of system components are not considered. Additionally, the indirect emissions of hybrid systems, particularly those related to the import of electricity produced from fossil fuels, have not been taken into account. Finally, although renewable energy technologies are less harmful compared to fossil fuels, they may still have environmental consequences, such as acoustic pollution and visual impact.

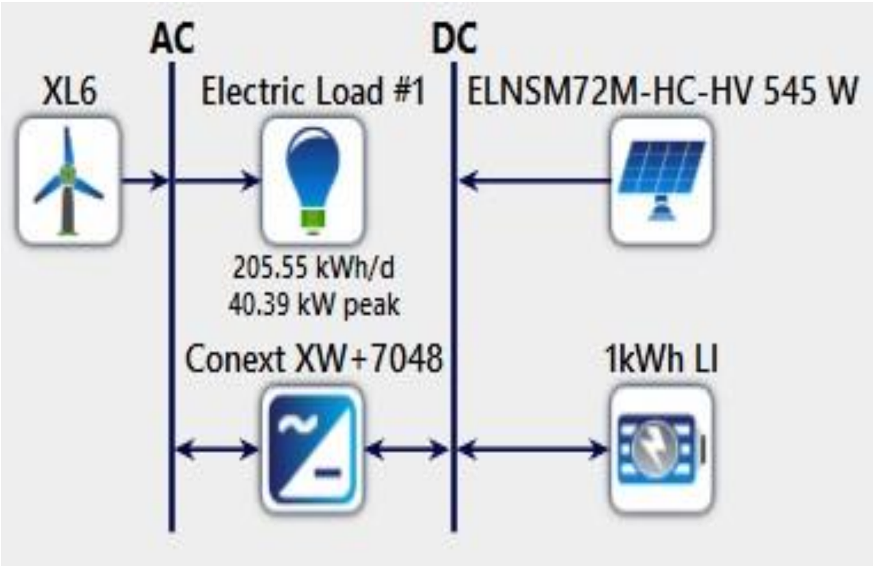

Figure 6. Hybrid system operating scenario

Table 6. PV+Storage, Wind+Storage system results

System No	**1**	**2**	**3**
PV System Power (kW)	96,7	618	-
Turbine Count	2	-	105
1 kWh Li-Ion Battery Count	198	257	257
Converter Power (kW)	35.8	61	61
Initial Investment Cost ($)	186.689	415.780	976.930
LCOE ($/year)	0,316	0,626	1,94
Operation & Maintenance Cost ($/year)	9.301	12.052	69.861
Net Present Cost ($)	306.928	607.579	1.088.000
Renewable Fraction	100%	100%	100%

4.1 Cash flow and cost summary for the selected scenario

HOMER software utilises the Total Net Present Cost (NPC) approach to determine the life cycle cost of the system being evaluated. This includes the balance of income and expenditure over the entire life of the project, adjusted to present value. Total NPC takes into account the initial investment cost, replacement costs and operation and maintenance costs. It also takes into account the cost of electricity purchased from the grid. Table 7 presents an analysis of the net present cost for the optimal system.

4.2 Production values

75.019 kWh of the electricity generated by the system was used for the annual demand of the residential area (to meet the entire demand). Additionally, 110.586 kWh of excess energy was produced. Excess electricity is the production of electricity exceeding the current demand in either a power grid or an off-grid system. This excess production accounts for 58.2% of the total production of the hybrid system. The unmet electricity demand throughout the year is 7.24 kWh, which corresponds to 0.097% of the total electricity demand.

Table 7. Net present cost analysis for the optimal system

Component	Initial Investment Cost ($)	Replacement Cost ($)	Operation & Maintenance Cost ($)	Salvage Value ($)	Total NPC ($)
Bergey Excel 6	15.300	4.877	12.410	-2.748	29.839
ELNSM72M HC-HV	43.501	0,00	2.499	0,00	46.001
Generic 1kWh Li-Ion	108.900	46.203	51.192	-8.695	197.600
Schneider Conext XW+70	18.987	16.774	0,00	-2.274	33.487
System	186.689	67.855	66.102	-13.719	306.928

Table 8. Annual production values of system components

Production Type	Production Value (kWh/year)	Production Share (%)
PV Solar Energy	152.296	80.1
Wind Energy	37.857	19,9
Total	190.153	100

4.3 Wind energy results

The values of electricity produced from PV solar, wind, and the total electricity produced by the optimal hybrid system are shown in Table 9, and the monthly production values are illustrated in Figure 7. The initial investment cost of the converter used in the simulation is $530, with a replacement cost of $530, and an annual operation and maintenance cost of $0.

Figure 8 illustrates how the energy density produced by the wind turbines is distributed over time. Compared to PV solar energy systems, the wind energy system has a higher energy density. PV solar energy systems are more reliable in meeting load demand because their primary resource is the sun, which is a more predictable source compared to wind.

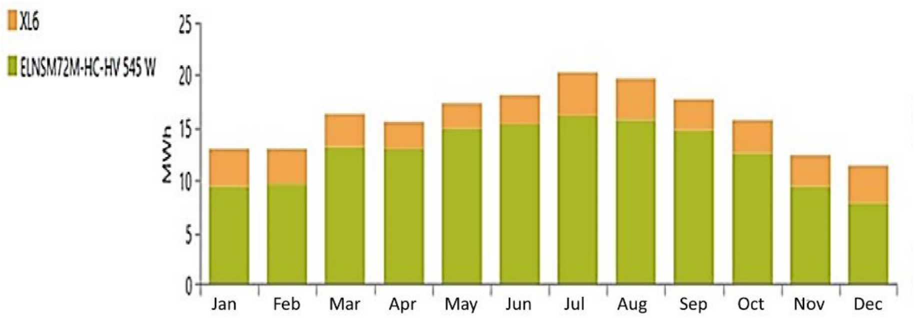

Figure 7. Monthly production values of system components

Table 9. Data for wind turbine

Parameter	Value
Total Installed Capacity	12 kW
Average Output Power	4,32 kW
Capacity Factor	36%
Total Production	37.857 kWh/year
Maximum Output Power	13,3 kW
Operating Hours	8.157 h/year
LCOE	0,061 $/kWh

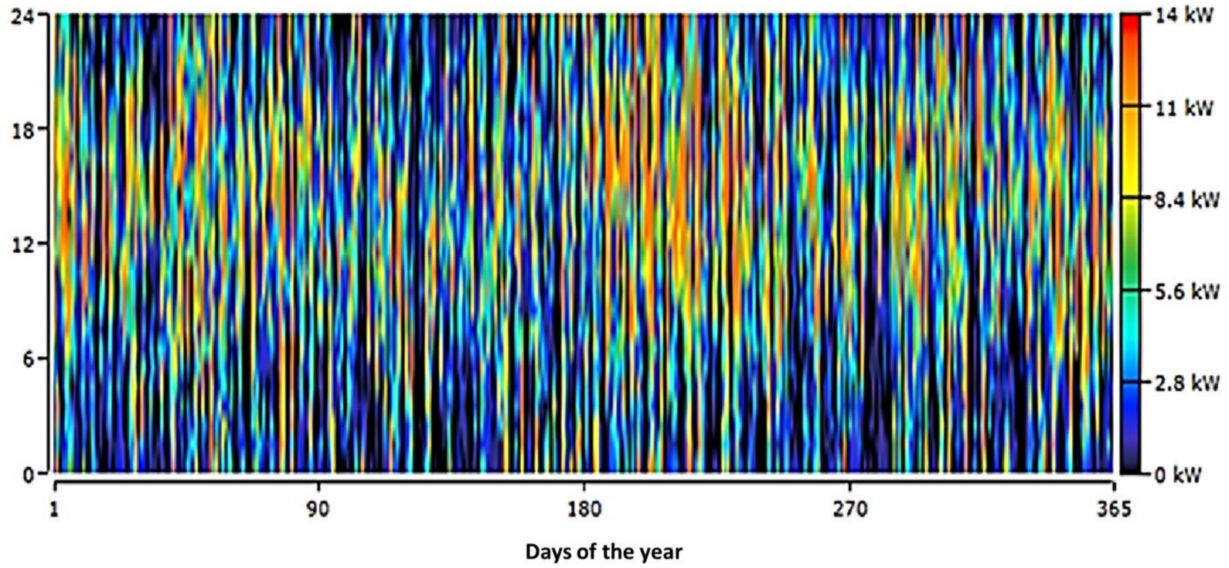

Figure 8: Power output density for wind energy

4.4 Solar energy results

The total PV solar energy power for the discussed optimal hybrid energy system is 96.7 kW. The PV solar energy produced 152,296 kWh of energy for this simulation. It accounts for 80.1% of the annual production. The data obtained for the PV system is examined in Table 10.

Table 10. Data for solar energy system

Parameter	Value
Total Installed Capacity	96,7 kW
Average Output Power	17,4 kW
Capacity Factor	18%
Total Production	152.296 kWh/year
Maximum Output Power	99,1 kW
Operating Hours	4.388 h/year
LCOE	0,0234 $/kWh

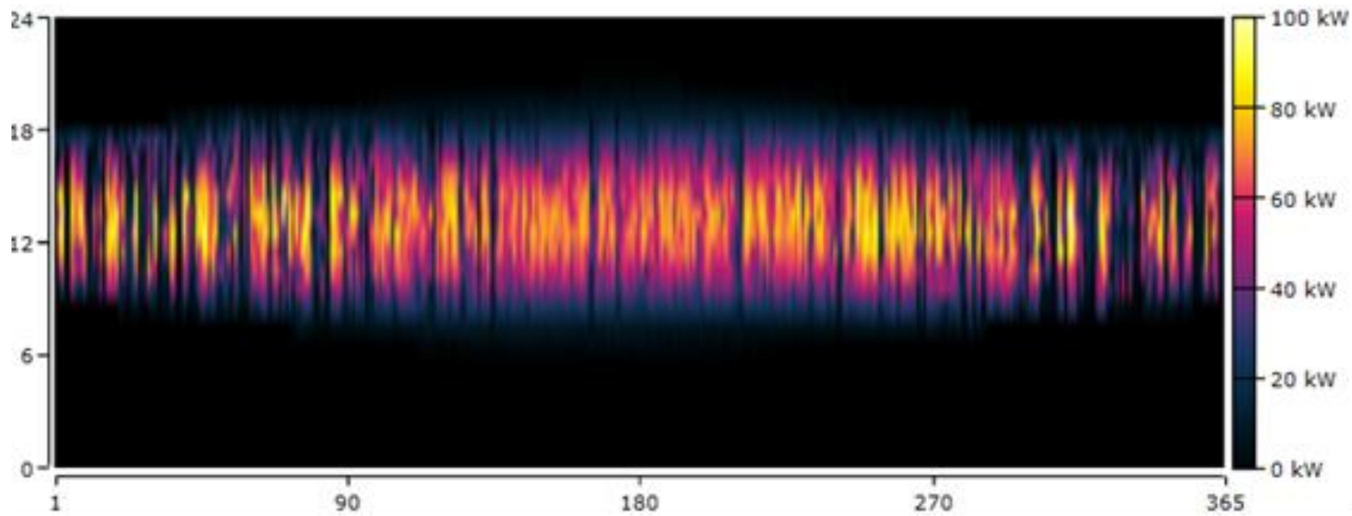

Figure 9. Power output density for solar energy system

4.5 Storage system results

The simulation results for the storage system of the optimal hybrid energy system are presented in Table 11.

Table 11. Data for solar energy system

Parameter	Value
Autonomy Duration	18,5 hrs
Nominal Storage Capacity	198 kWh
Usable Storage Capacity	158 kWh
Lifetime Efficiency	356.062 kWh
Annual Energy Input	24.986 kWh/yr
Annual Energy Output	22.519 kWh/yr
Capacity Depletion	33,5 kWh/yr
Losses	2.500 kWh/yr

4.6 Inverter results

The simulation results for the converter of the optimal hybrid energy system are presented in Table 12. The data from the simulation indicate that the capacities of the inverter and rectifier are quite close to each other. The average output power for the system remained low compared to the capacity, which is due to the wind turbines directly feeding the AC bus.

Table 12. Data for the inverter system

Parameter	Inverter	Rectifier	Unit
Capacity	18,5	34,4	kW
Average Output Power	5,13	0,295	kW
Min. Output Power	0	0	kW
Max. Output Power	35,8	10,7	kW
Capacity Factor	14,3	0,856	%
Operating Hours	6.701	949	hrs/yr
Energy Output	44.912	2.580	kWh/yr
Energy Input	46.881	2.693	kWh/yr
Losses	1.969	113	kWh/yr

5 Conclusion

In this study, the goal was to meet the electricity needs of a settlement in western Turkey using an off-grid solar-wind hybrid energy system. The HOMER software was utilized to optimally size the system, which combines solar energy, wind energy, and storage components. The advantageous location of the region, with its high solar and wind energy potential, played a significant role in enabling the design.

The current global trends in renewable energy were also reviewed. The continuous decrease in the costs of solar and wind energy systems since 2010 has significantly boosted their adoption. However, achieving the renewable energy capacity necessary to mitigate climate change remains a major challenge. This underscores the urgent need to phase out fossil fuels and accelerate the transformation of energy systems.

Optimization results indicate that the PV + wind hybrid system achieves the lowest energy cost, outperforming wind-only and PV-only configurations. The optimal system configuration includes a 96.7 kW PV array, 12 kW wind turbines, a 198 kWh battery bank, and a 35.8 kW converter. The financial analysis reveals an initial investment cost of $186,689, a replacement cost of $67,855, operation and maintenance costs of $66,102, and a total net present cost of $306,928.

The findings highlight the importance of hybrid renewable energy systems in addressing energy needs while minimizing costs. The PV + wind hybrid configuration's superior performance stems from its ability to balance the intermittent nature of solar and wind resources, providing a more stable and reliable energy supply. In contrast, single-source systems, such as PV-only or wind-only, require larger storage capacities and exhibit higher overall costs, limiting their practicality in off-grid applications.

These results also emphasize the potential scalability of hybrid systems. While this study focused on a specific settlement, similar systems can be adapted to other regions with varying renewable resource potentials. The flexibility in design and the continuous decline in the cost of renewable technologies suggest that hybrid systems could play a pivotal role in the global energy transition.

Additionally, the study underscores the broader implications for energy policy. Investments in hybrid renewable energy systems could reduce dependence on fossil fuels, contribute to energy security, and mitigate greenhouse gas emissions. Policymakers should prioritize incentives and infrastructure development to support the widespread adoption of such systems, not only in remote areas but also in urban environments.

In conclusion, this study demonstrates that hybrid renewable energy systems are a cost-effective and sustainable solution for meeting energy demands. Moving forward, integrating such systems into national energy strategies and expanding their application to diverse geographic contexts will be crucial for achieving global sustainability goals.

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