FEASIBILITY AND OPTIMIZATION OF HYBRID ENERGY SYSTEMS IN THE SAKARYA–KARASU REGION: A CASE STUDY

Asst. Prof. Dr. Aykut Fatih Güven,
Yalova University, Faculty of Engineering,
Necat Uzuner
Yalova University, Faculty of Engineering,

ABSTRACT
Energy resources have been a critical research area throughout human history. Since the industrial revolution, the economic advantages and advanced production technologies of fossil fuels have increased their utilization. However, the limited lifespan and environmental impact of fossil fuels have significantly heightened interest in renewable energy sources. This study examines the potential for meeting the electrical and thermal needs of 462 households and 1848 residents in the Sakarya Karasu district with an off-grid hybrid energy system. Using the energy demands of the residences and the region’s meteorological data, a hybrid energy system model integrated with solar and wind energy was developed using HOMER Pro software. The model is complemented by a diesel generator to ensure energy continuity. The cost analysis determined that the system's installation cost was $2,303,319.44, with an operational cost of $415,969.60 and a total net present cost of $10,358,090.00. The unit energy cost was calculated as $0.327/kWh. Sensitivity analyses highlight the economic and environmental benefits of hybrid energy systems in terms of effective battery utilization, waste heat recovery from generators, and optimized system costs. This study presents significant findings on the feasibility of implementing hybrid energy systems in off-grid areas and their potential to reduce dependence on fossil fuels.
Keywords: Techno-Economic Analysis, Hybrid Energy Systems, Renewable Energy, HOMER Pro Software, Energy Optimization.

INTRODUCTION
Energy resources have been a fundamental subject of research since ancient times. With the Industrial Revolution, the demand for energy increased rapidly, pushing the use of fossil fuels to its peak. Today, the majority of energy needs are met by fossil fuels such as coal, oil, and natural gas. However, the oil crisis of the late 20th century shook confidence in fossil fuels and spurred interest in renewable energy sources (Güven & Poyraz, 2017).
Renewable energy sources play a critical role in sustainable energy production. Sources such as solar, wind, hydroelectric, biomass, and geothermal energy have low environmental impacts and are not at risk of depletion. However, the intermittent and variable nature of these sources poses challenges in terms of ensuring the continuity of energy production (Kaldellis, Kondili & Filios, 2006). Hybrid energy systems have been developed to overcome these challenges. Hybrid energy systems combine multiple renewable energy sources. For example, the limited availability of solar energy during daylight hours and the inconsistency of wind can complicate their independent use. However, high-capacity storage systems can be used to store energy when production is not possible (Khalil et al., 2022).
Turkey has significant potential for renewable energy sources, particularly solar and wind energy. The average annual sunshine hour is 2,640 hours, equivalent to a daily average of 7.2 hours. Turkey’s wind energy potential is estimated to be approximately 48 GW. This potential can meet a substantial portion of Turkey’s energy needs and reduce its dependence on fossil fuels (İller Bankası, 2024).
The HOMER (Hybrid Optimization Model for Electric Renewables) software is widely used for designing and optimizing hybrid energy systems. HOMER Pro simulates various configurations of renewable energy systems, considering factors such as cost, efficiency, and environmental impact. This

software not only performs technical and economic analyses but also conducts sensitivity analyses to identify critical factors affecting system performance. These capabilities make HOMER Pro a valuable tool for researchers and engineers (Güven & Mete, 2021).

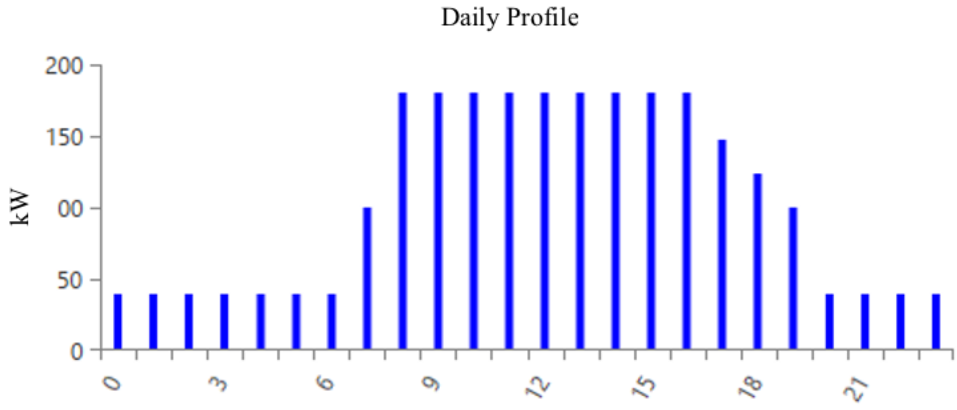
Recent HOMER Pro studies have highlighted the effectiveness and economic advantages of hybrid energy systems. For instance, Chowdhury et al. (2023) designed a hybrid energy system that integrates solar and wind energy in a rural area of South Korea, emphasizing the system's cost-effectiveness and reliability. In their 2022 study, Güven and Mete designed and compared various hybrid energy systems. The scenarios included grid connections, solar panels, wind turbines, diesel and biogas generators, fuel cells, electrolyzer, hydrogen tanks, batteries, and converters. The most cost-effective and environmentally friendly system was the grid-connected Solar Panel/Wind Turbine/Biogas Generator/Battery hybrid, with a net present cost of $176 million, a unit energy cost of $0.0301, and 100% renewable energy production.

In another study, Prasad and Natarajan (2006) explored the cost-effectiveness of a hybrid solar and biomass energy system in a rural area of India. Rehman (2021) identified wind/solar-PV, wind/solar-PV/diesel, and solar-PV/diesel combinations as the most effective combinations for supplementing Saudi Arabia's energy portfolio, with average energy costs of $0.458, $0.355, and $0.349 per kWh, respectively. Diaf et al. (2008) conducted a cost analysis of a hybrid energy system supported by solar and wind energy in Algeria and evaluated the system performance using HOMER Pro.

This study examines the potential of meeting the electrical and thermal needs of a community of 462 households and 1,848 people in the Karasu district of Sakarya using an off-grid hybrid energy system. Based on the energy demands of households and the meteorological data of the region, a hybrid energy system model integrating solar and wind energy was created using HOMER Pro software. The model was supplemented with a diesel generator to ensure energy continuity. After conducting cost analyses of the created system, sensitivity analyses were performed by considering parameters such as the activation of the generator at different operational loads, utilization of waste heat from the generator in a cogeneration system, increasing the height of the wind turbine tower, and changes in diesel prices. The effects of thermal load control and battery usage on the system were investigated both economically and technically. After reviewing all optimizations and sensitivity analyses, potential cost reductions were evaluated.

MATERIALS AND METHODS

The initial implementation of this study was performed in the Karasu district of Sakarya province, Turkey (41°6.8' N 30°40.6' E). The research was conducted in a community consisting of 462 households and a total of 1848 people. According to studies by TEİAŞ, the average daily electricity consumption of a four-person household is approximately 8 kWh. Therefore, the total daily electricity needs of 462 households are calculated to be 3696 kWh. The electricity consumption profile tended to be higher in the evening hours, and the predefined community load profile (Figure 1(a)) in HOMER Pro software was used in this study. The total daily electricity consumption was 3696 kWh, with a peak power consumption of 473.83 kW observed during the day (Figure 1(b)). The system is designed not only to meet the electrical load requirements but also to address the thermal load needs of households. The average heat loss per square meter is determined to be 13.761 kWh, and assuming an average house size of 100 square meters, the annual heat loss per house is calculated to be 1376.1 kWh. For a community of 462 households, the annual total thermal energy requirement was found to be 635761.58 kWh. The thermal load requirement varies seasonally, with the majority occurring in winter. The thermal load profile shown in Figure 1(c) and Figure 1 (d) was accordingly integrated into the system. The thermal load requirements are 27.18% in January, 17.85% in December, 24.70% in February, 11.75% in March, 7.43% in November, 8.70% in April, and 2.39% in October, with no thermal load requirements for the remaining months. HOMER Pro software was used for the analysis and optimization of both the electrical and thermal load profiles, with the load data detailed on an hourly basis throughout the year. These profiles play a critical role in system design and performance evaluation (Güven & Yörükeren, 2022).



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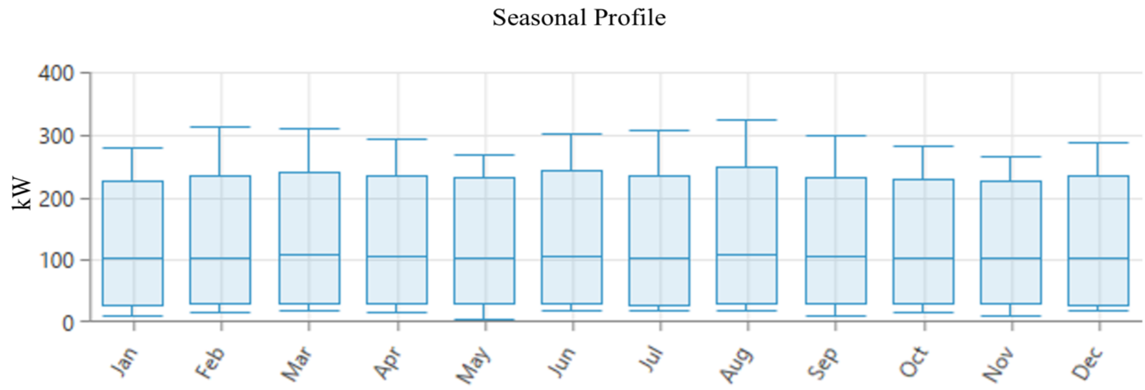

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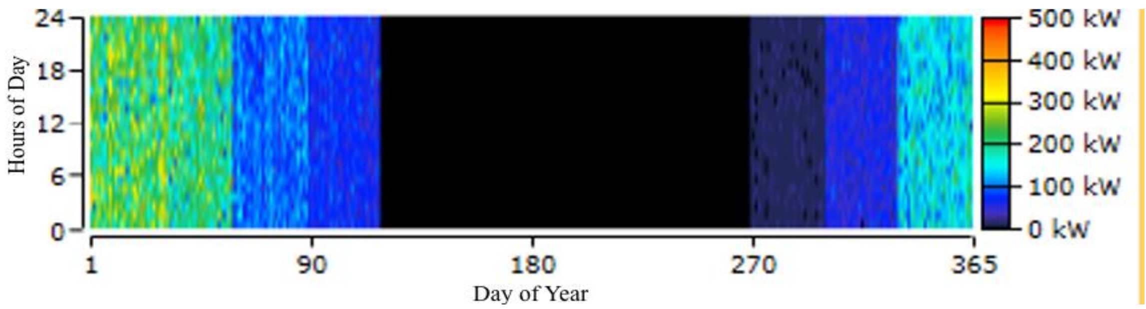

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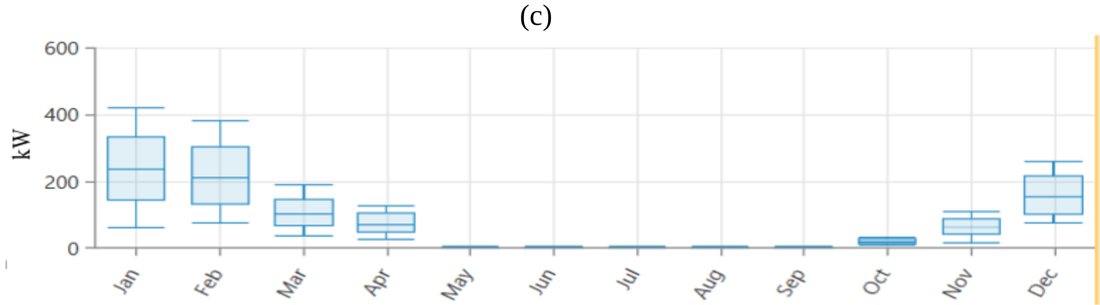
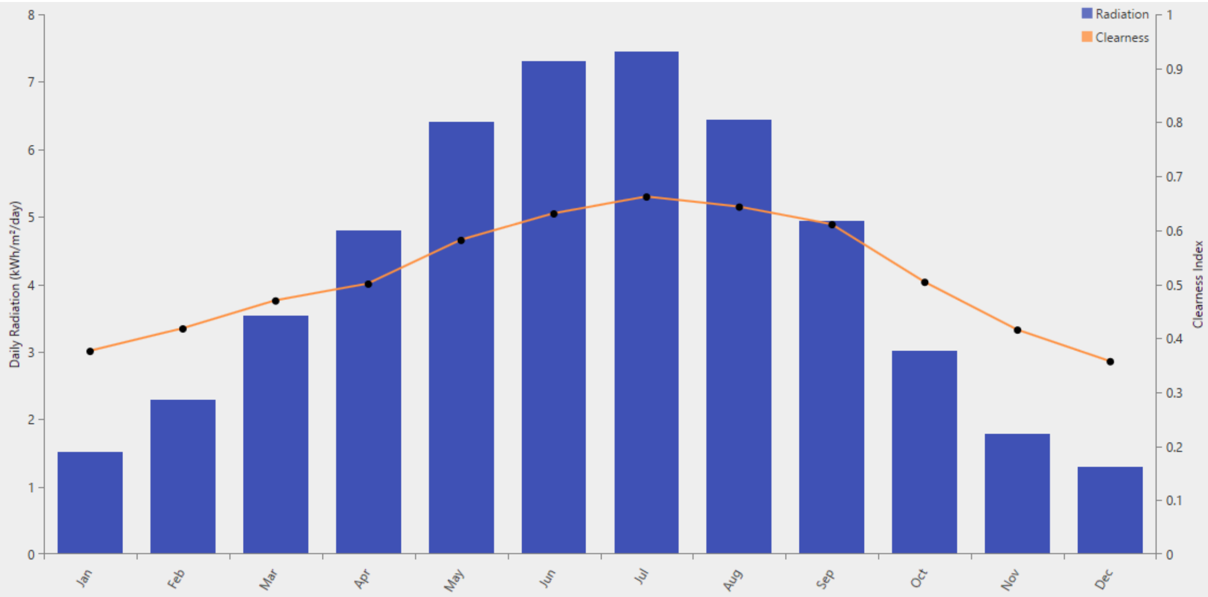


(d)

Figure 1. Load profiles (a) hourly (b)montly (c) thermal load (d) monthly distribution of thermal load requirement.

The potential for solar panels to generate electricity from solar energy is directly proportional to the meteorological conditions of the region (Güven & Hatipoğlu, 2022). The solar energy data for the region were integrated into HOMER Pro software from NASA’s database. These data were obtained from measurements taken over 22 years, from July 1983 to July 2024, and averaged. According to Figure 2 (a) , the region’s solar energy potential increases during the summer months and decreases during the winter months, with an annual average daily solar energy potential of 4.23 kWh/m².
Given the high investment costs of wind turbines, the wind speed profile of a region is crucial for their deployment. The wind speed profile for the region was also obtained from NASA’s database, which showed an average wind speed of 4.85 m/s. These wind speed data were based on 29 years of measurements taken at a height of 50 m from January 1983 to January 2024. The region's wind speed profile is illustrated in Figure 2 (b). It is evident that wind energy can serve as a complementary source during winter when solar energy is insufficient, and the synergistic effect of these two energy sources makes them among the most commonly used energy sources in hybrid systems.
Another important meteorological parameter for the region was temperature, which was also obtained from NASA's database. These data represent the average of 29 years of measurements taken between January 1983 and January 2024. As shown in Figure 2 (c), the temperature profile is higher during summer than during winter. The average temperature over the 29-year measurement period was 13.93°C.



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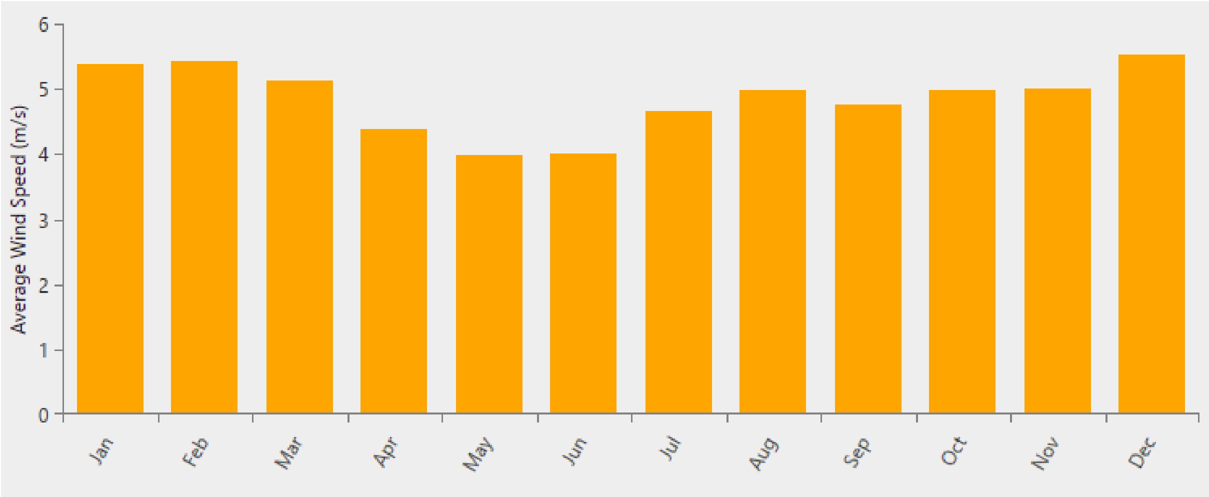

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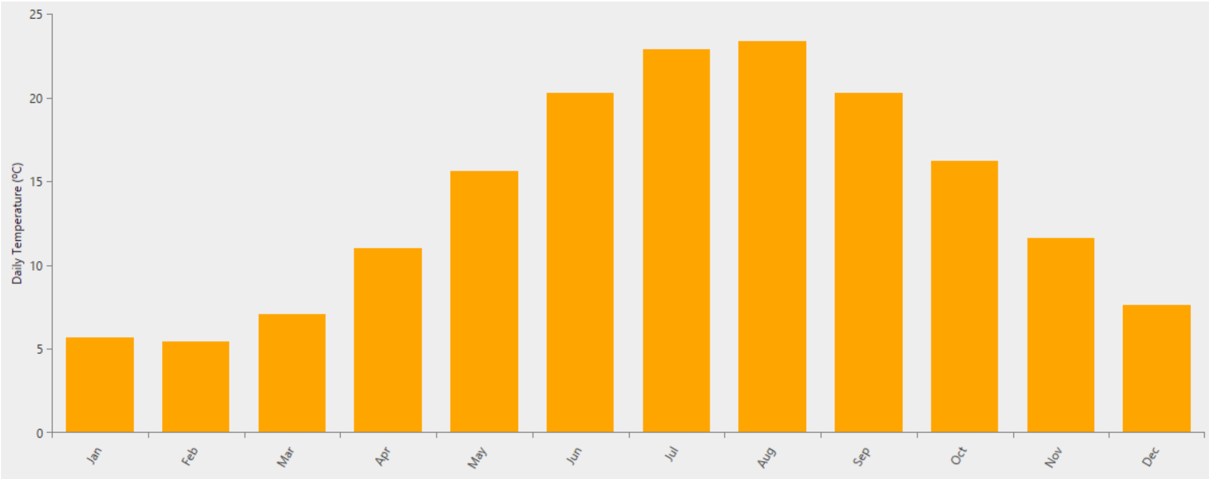


(c)

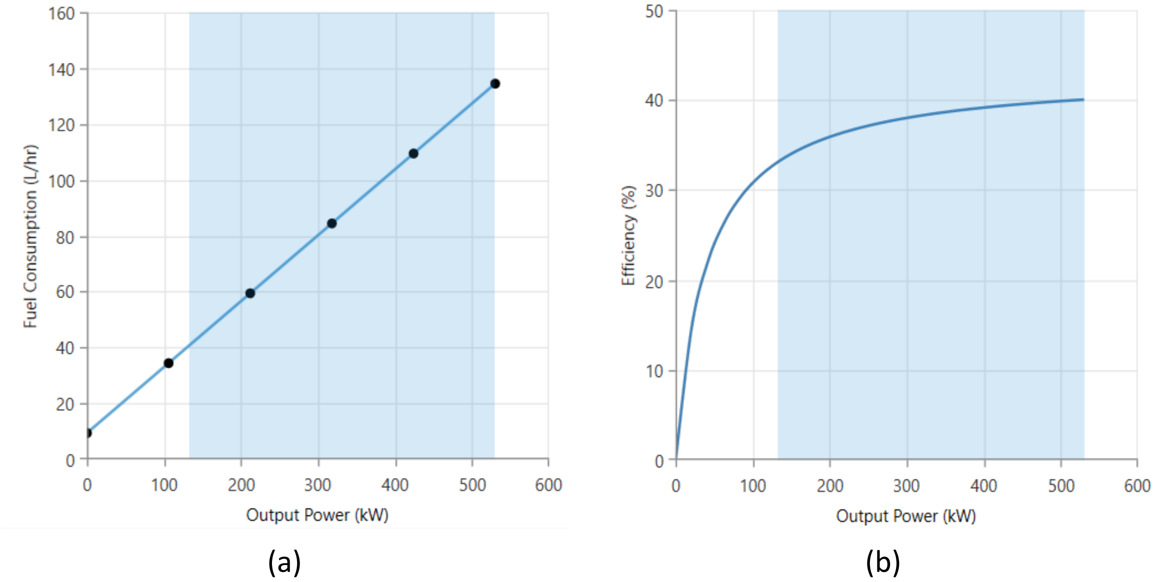
Figure 2. Meteorological data (a) solar radiation (kWh/m^2/day), (b)wind speed (m/s), (c) ambient temperature(^{0}C).

Hybrid energy system components

Diesel Generator

According to previous research, the cost of diesel generators typically ranges from $250 to $500 per kW. For the diesel generator used in this project, a cost of $400/kW was considered. The price of diesel generators generally decreases inversely with capacity, meaning that generators with larger capacities have lower costs per kW. The fuel consumption and efficiency curves of the generators used in the hybrid energy system are presented in Figures 3(a) and (b). It can be seen that operating the generator close to its rated capacity improves efficiency and reduces the consumption of fuel per kW. In this study, the price of diesel fuel is assumed to be $1.27 per liter.

Figure 3. Diesel generator profiles: (a) fuel consumption (b) efficiency



Here, to model the fuel consumption of the generator, a linear Equation (1) is used:

$$F_{DG} = a_1 P_{DG} + a_0 P_{DGR}$$
(1)

In this equation, F_{DG} represents the fuel consumption of the generator (in liters per hour, a_0 is the fuel cut-off coefficient (in liters per hour per kilowatt, P_{DGR} is the capacity of the generator in kilowatts, a_1 is the slope of the fuel curve (in liters per hour per kilowatt, and P_{DG} is the power output in kilowatts (Güven & Yücel, 2023).

Wind Turbine

One of the most suitable systems for reducing unit energy costs is the wind turbine system. However, due to high installation costs, low-capacity wind power systems are not economically viable (Nasser & Hassan, 2024). According to previous research, the installation cost of a wind turbine system is approximately $2000 per kW. The wind turbine used in the system has a capacity of 10 kW and an installation cost of $20,000. In addition to the installation cost, the replacement cost is $20,000, and the annual maintenance cost is $300. The power–speed curves for the respective wind turbines are shown in Figure 4.

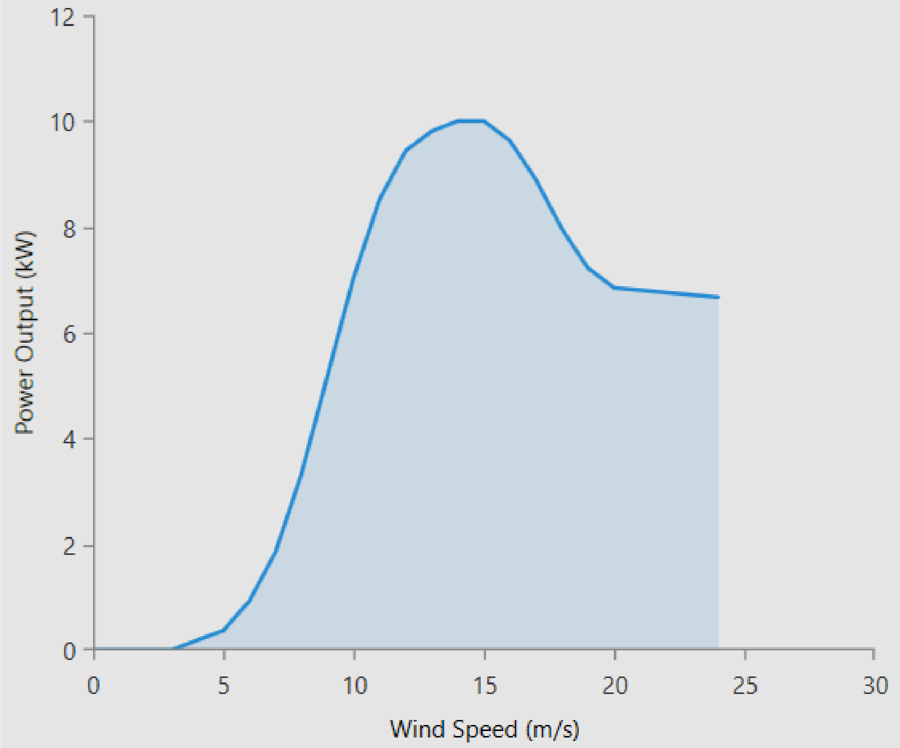


Figure 4. Power–speed curve of the wind turbine

$$P = \frac{1}{2} p C_p A v_\omega^3$$

(2)

Equation (2) generally describes the relationship between the wind speed and the electrical output of a wind turbine. The relevant parameters typically include the swept area (A), air density (p), and wind speed (v). These factors together determine how efficiently a wind turbine can convert wind energy into electrical energy, depending on the specific design and environmental conditions (Güven et al., 2023).

Photovoltaic Panel

Solar panels are used to directly generate electrical energy from sunlight without the need for any moving mechanisms. Solar energy is one of the most important renewable energy sources capable of significantly meeting global energy demand. The panel used in the system is one of the integrated panels in HOMER Pro software, focusing on the critical parameter of cost per watt (Mussard et al., 2023). Currently, solar panel prices are around 35 cents per watt, with installation costs for solar panel systems typically around $1500/kW and replacement costs also approximately $1500/kW. The annual repair and maintenance cost was $20, which was used as a reference in the calculations.

The power output of a PV panel can be mathematically described by Equation (3):

$$P_{PV} = Y_{PV}\, f_{PV} \left(\frac{G_T}{G_{T,STC}}\right) \left[1 + \alpha_f \left(T_C - T_{C,STC}\right)\right] \quad (3)$$

In Equation (3), P_{PV} (W) represents the current power output of the photovoltaic system. Y_{PV} (W) is the standard output power of the PV system under standard test conditions (STC), while f_{PV} (%) is the adjustment factor applied to account for real-life conditions affecting the PV system. G_T (W/m²) represents the solar irradiance incident on the PV module at any given moment, and $G_{T,STC}$ (1000 W/m²) represents the assumed irradiance under the STC at 25°C. The temperature coefficient of the PV module, α_f (%/°C), typically ranges from 0.3% to 0.5%, indicating the sensitivity of the PV output to temperature changes. T_C (°C) denotes the current temperature of the PV module, while $T_{C,STC}$ (°C) refers to the temperature of the PV module under the STC, which was set to 25°C (Güven and Poyraz, 2021).

When HOMER Pro software ignores the impact of the temperature coefficient [$\propto_f$ (%/°C)] on PV system performance, an alternative calculation method is used. This method, referred to as Equation (4), simplifies the process when the effects of temperature are minimal or when the precise impact of temperature variations is not significant (Güven, 2023a).

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T\,STC}}\right)$$

(4)

Batarya (BT)

In HOMER Pro software, battery modeling involves several key equations that describe the performance and behavior of a battery system. The primary equations used for battery modeling include the state of charge (SOC), charge and discharge efficiency, and the depth of discharge (DOD).

The system utilizes lithium-ion batteries with a capacity of 1 kWh each, and the cost is $350 per kWh. Similarly, the replacement cost is approximately $350 per kWh. The annual repair and maintenance cost is $25. The discharge depth, which significantly affects the number of battery cycles, was assumed to be 80%.

State of Charge (SOC)

SOC of a battery at any time t is given by Equation (5).

$$\mathrm{SOC}(t) = \mathrm{SOC}(t-1) + \left(\frac{P_{in}(t) - P_{out}(t)}{C_{Bat}}\right)$$

(5)

Where $\mathrm{SOC}(t)$ is the state of charge at time t, $\mathrm{SOC}(t-1)$ is the state of charge at the previous time step, $P_{in}(t)$ is the power input to the battery at time t (charging), $P_{out}(t)$ is the power output from the battery at time t (discharging), and C_{Bat} is the capacity of the battery (Güven, 2023b).

Charge and Discharge Efficiency

The efficiency of the battery during charging (η_{charge}) and discharging ($\eta_{discharge}$) affects the net energy stored and retrieved by the battery:

$$E_{stored} = P_{in} \times \eta_{charge}$$

(6)

$$E_{retrieved} = P_{out} \times \eta_{discharge} \tag{7}$$

where E_{stored} is the effective energy stored in the battery and $E_{retrieved}$ is the effective energy retrieved from the battery.

Depth of Discharge (DOD)

The depth of discharge (DOD) represents the fraction of the battery capacity that has been used and is calculated as Equation (8):

$$DOD = 1 - SOC$$

(8)

Battery Life Cycle

The battery life cycle depends on the DOD and the number of charge–discharge cycles:

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$$L_{Battery} = \frac{N_{cycles}}{DOD}$$

(9)

Where $L_{Battery}$ is the battery life in terms of the number of cycles, and N_{cycles} is the total number of charge–discharge cycles that the battery can undergo. These equations collectively describe the behavior of the battery system in HOMER Pro, allowing for the simulation and optimization of battery performance within energy systems.

Bidirectional Converter

An inverter converts direct current (DC) to alternating current (AC). Although many electronic devices and systems operate on DCs, homes, businesses, and general power infrastructures typically use ACs. In this context, inverters play a crucial role in the conversion of energy from DC to AC. Inverter technology is used in a wide range of applications, from small-scale portable devices to large-scale solar and wind energy systems. Depending on their functions and areas of use, various types and features of inverters are available. The primary function of the inverters is to efficiently convert the DC input to the AC output, which is critical for achieving high energy efficiency. Some inverter models also provide additional functions such as voltage and frequency adjustments (Güven & Poyraz, 2021). In this system, the installation and replacement costs of the inverter are set at $300, with an annual maintenance cost of zero dollars and a projected lifespan of 15 years. The inverter capacity is then determined by Equation (10):

$$P_{inv} = \frac{E_{L,max}}{\eta_{DC/AC}} \quad (10)$$

In Equation (10), P_{inv} (W) represents the capacity of the power inverter, $E_{L,max}$ (Wh) denotes the peak energy demand of the load, and $\eta_{DC/AC}$ signifies the efficiency rate of the conversion from DC to AC (Singh and Kumar, 2023).

Thermal Load Controller

A thermal load controller (TLC) establishes a connection between a thermal load system and an electrical load system. Excess energy produced in the electrical system is transferred to the thermal load bus, preventing excessive energy use for heating. The cost per kW of the thermal load controller was calculated based on the $200 specified in HOMER Pro.

Boiler

HOMER pro software uses a boiler system to meet thermal loads and consumes diesel fuel as its energy source. The efficiency of the boiler used in the system was set at 85%.

Economic Analysis Inputs

The HOMER Pro software uses the annual real interest rate to calculate cost. The real interest rate is determined using the current interest rate and the inflation rate. The annual real interest rate is calculated using Equation (11):

$$i = (i' - f)/(1 + f) \ (1)$$

(11)

Where i represents the annual real interest rate, f is the annual inflation rate, and i' is the current interest rate. In this study, the current interest rate is assumed to be 42.50%, and the inflation rate is 39.61%. From these values, the real interest rate was found to be 2.07%.

HOMER Pro simulation of Hybrid Renewable Energy System and Results

HOMER Pro is reliable software widely used for the sizing and optimizing of multiple energy sources, and it is also known as a hybrid optimization program. The software assists in performing a preliminary feasibility test for various RE configurations of different sizes and sensitivity analysis for different configurations of the desired energy systems. The software was developed by the US National Renewable Energy Laboratory (NREL) for grid-connected and off-grid applications. It runs on a Windows platform and is programed in C++ (Güven & Mengi, 2023).

Designing and configuring a microgrid involves a critical decision-making task in terms of component size, component design, and selection of a suitable location. The inflation rate, interest rate, and other technical specifications of the selected components are necessary for the cost assessment of these hybrid energy systems. Regarding decision-making, there are many options, depending on technology and the availability of energy sources.

HOMER Pro integrates optimization and sensitivity algorithms, thus simplifying the evaluation process. The optimal simulations adhere strictly to user-specified constraints, thereby minimizing the NPC value. Beyond performing energy balance assessments, HOMER Pro filters out infeasible designs and highlights viable configurations that guide users toward determining an ideal system blueprint. Moreover, this simulation rigorously examines a system's technical viability, ensuring that it addresses both electrical and thermal demands within the set constraints. The proposed platform also delves into the system's NPC, factoring in costs related to installation and ongoing maintenance. Spanning a full year or 8760 hours, HOMER Pro's simulation yields results in a structured table, supplemented with illustrative graphs and charts. These visualizations delineate technical and economic metrics, elucidate the techno-economic dynamics, and permit comparisons among hybrid energy system designs. The output is export ready for deeper analysis. The core elements of optimization include decision parameters such as PV dimensions, wind turbine count, battery numbers, and converter capacity; inclusion of renewable resources such as PV arrays and wind turbines; generator magnitude; and dispatch blueprint dictating operational strategies.

Figure 5 presents a concise schematic of the hybrid renewable energy systems, and Figure 6 presents a comprehensive flowchart detailing each phase of the HOMER Pro simulation process. The designed microgrid, as shown in Figure 5, is intended to meet both the electrical and thermal load requirements.

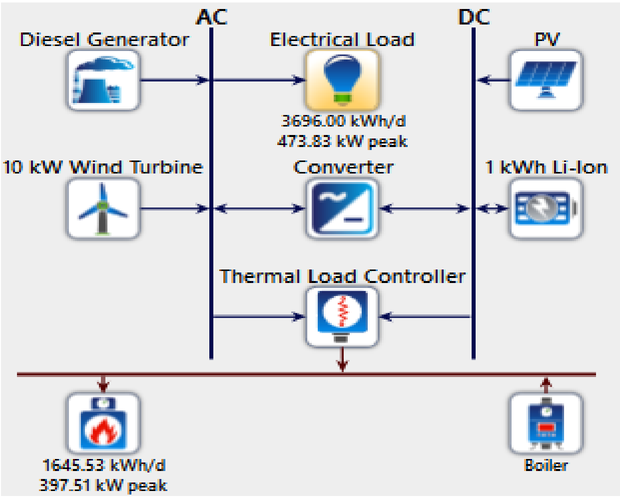

Figure 5. A schematic of the hybrid renewable energy system configuration was created using HOMER Pro software**.**

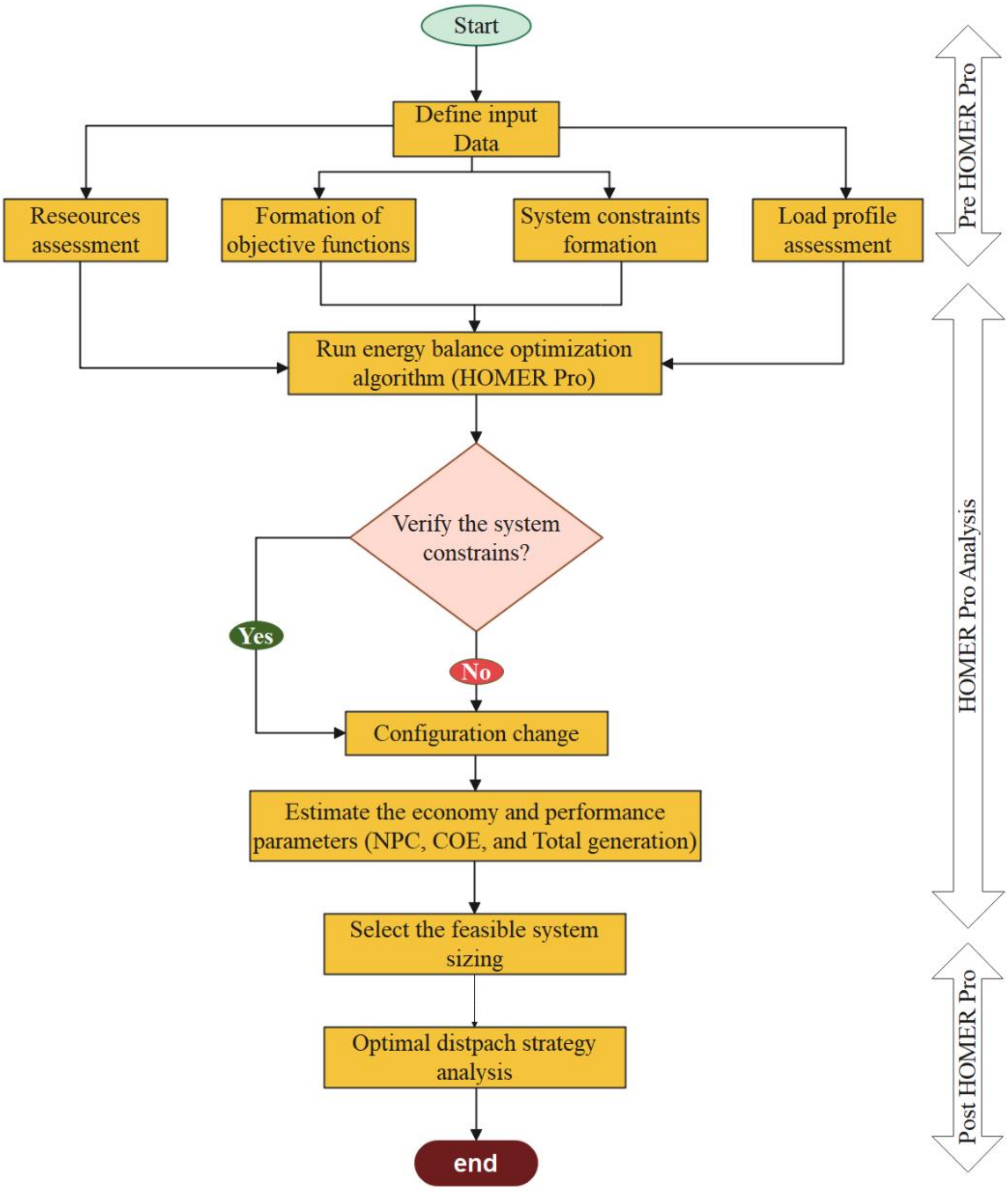

Figure 6. HOMER Pro optimization flow diagram.

RESULTS AND DISCUSSION

The simulations have led to the development of several potential systems that can be implemented in the region. Table 1 lists the results obtained by the four most suitable systems. The analyses utilized the region's meteorological data, with the diesel price assumed to be $1.27 per liter and the wind turbine height set at 24 meters. It was assumed that the generator only produced electricity with a generator startup load of 25%, and the scenarios considered constant system loads.

The simulation results show that the designed systems can effectively meet both the electrical and thermal load demands of the region. The comparison of different systems highlights the trade-offs between various configurations in terms of cost, efficiency, and sustainability. By analyzing these factors, it becomes evident that optimizing the balance between renewable and conventional energy sources is crucial for achieving both economic and environmental benefits.

The results indicate that incorporating renewable energy sources, such as wind turbines and solar panels, significantly reduces the dependency on diesel generators, leading to lower operational costs and reduced carbon emissions. The inclusion of a thermal load controller further enhances system efficiency by utilizing excess electrical energy for heating, thereby minimizing energy wastage.

Moreover, the economic analysis underscores the importance of considering both installation and maintenance costs along with real interest rates to accurately evaluate the financial viability of the proposed systems. The calculated real interest rate of 2.07%, based on current interest and inflation rates, provides a realistic perspective on long-term investment and saving potential.

Table 1. Simulation results obtained using HOMER Pro.

PV panel (kW)	594	625	0	0
Wind Turbine (kW)	6	0	13	0
Diesel Generator (kW)	530	530	530	530
Battery(kW)	2,340	2,156	417	1,109
Thermal Load Controller (kW)	100	100	100	100
Converter(kW)	416	597	267	144
Dispatch	LF	LF	CC	CC
Net present cost (NPC) ($)	$11.4M	$11.7M	$13.4M	$14.6M
Cost of Energy (COE) ($)	$0.37	$0.38	$0.45	$0.49
Operating costs ($/yr)	$475,418	$494,206	$655,995.00	$717,724.00
Initial Capital ($)	$2.19M	$2.10M	$717,953.00	$663,435.00
Ren Fraction (REF) (%)	42	36.9	0	0
Total fuel consumption (L/yr)	217,538	231,127	384,431	426,834

The simulation was conducted under specified parameters to identify the most suitable systems for the region. The optimal unit energy cost was found to be $0.369. In the first system, the configuration included a 594-kW solar panel, a 6-kW wind turbine, a 530-kW diesel generator, a 2340-kWh battery storage system, a 100-kW thermal load controller, and a 416-kW converter. In the second system, a wind turbine was omitted, which increased the solar panel capacity to 625 kW, decreased the battery storage system to 2156 kWh, and reduced the renewable energy factor from 39.7% to 36.9%.

The removal of wind turbines had significant impacts: it prevented the generation of electricity during winter periods when solar panels are less effective, increased the operational load on the generator, and consequently raised fuel consumption from 217,358 to 231,127 liters. The primary disadvantage of wind turbines is their high installation costs, which increase the initial investment. However, it also contributes to reducing the emission values, as detailed in Table 2.

Table 2. Emission values of the optimization result.

Value	Emission (kg/year)
CO2	605302
CO	2618
Unburned Hydrocarbons	114
Particulate Matter	15,9
SO2	1488
NOx	2459

A slight increase in the system's investment could facilitate the installation of a more environmentally friendly setup, reducing emissions while maintaining the same energy cost. Such enhancements should be considered in all systems to promote a sustainable world.

Impact of the Thermal Load Controller on the System

The thermal load controller significantly contributes to the system by recovering the excess electricity produced, thereby reducing the boiler's production and significantly lowering harmful gas emissions. As the primary power producers, photovoltaic panels generate excess energy during summer. However, during winter, the increased thermal load demand cannot be met by the excess energy produced by photovoltaic panels, as this excess energy cannot be utilized by the thermal load controller. To optimize the system's efficiency, it is recommended that the excess energy produced between May and October be utilized in various cooling systems. This could lead to a significant reduction in cooling energy consumption during summer. Figure 7 illustrates the surplus electricity produced and the thermal load demand throughout the year.

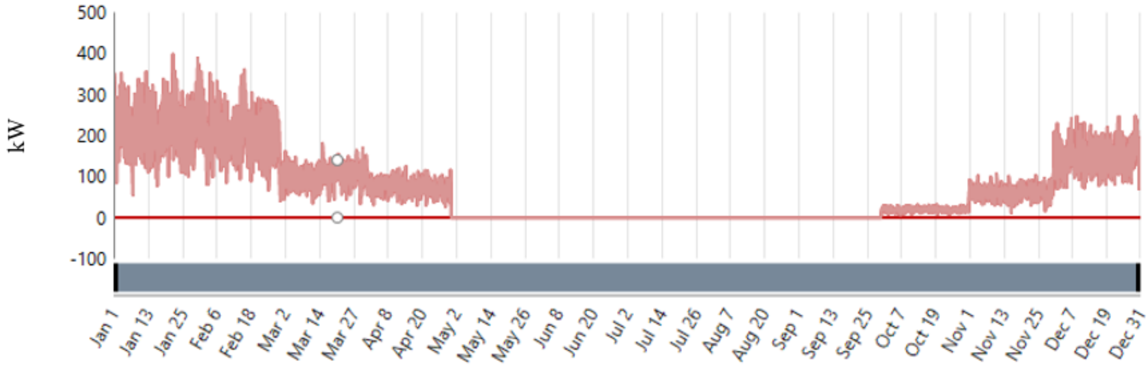

Figure 7. Surplus electricity produced and thermal load demand throughout the year.

Effects of Generator Performance Under Various Load Conditions

The simulation analysis performed the generator performance under different load conditions, which were categorized into three scenarios: 25%, 50%, and 75% load capacities. The analysis, conducted under scenarios of potential diesel price increases, showed that the unit energy cost could drop to $0.334/kWh if the generator operates at loads exceeding 75%. These results indicate that the generator's continuous high-efficiency operation results in lower fuel consumption and more cost-effective energy production. When operating at all load levels, the generator operated at an average capacity of 530 kW, consumed 161,885 L of fuel annually, and produced 587,032 kWh of electricity at an efficiency of 33.9%. However, when operating at a minimum of 75% capacity, the generator achieved an average capacity of 398 kW and an efficiency of 39.1%, indicating lower fuel consumption and higher electricity production. If diesel prices exceed $1.47 per liter, incorporating a wind turbine into the system is recommended.

Utilization of Generator Waste Heat

Generators generate significant heat loss during electricity generation, which can be harnessed through a cogeneration system to add an additional energy source to the system. The cogeneration system recovers the heat produced by the generator for use during thermal loads, thereby enhancing the energy efficiency. By increasing the heat recovery rate of the generator to 15%, the simulations indicate that the boiler fuel consumption can be reduced by 8,000 L annually. This also led to significant reductions in CO_2 and SO_2 emissions. The decreased fuel consumption also reduced the unit energy cost to $0.369. The impact of the generator's heat recovery rate on the unit energy cost and fuel consumption is illustrated in Figure 8.

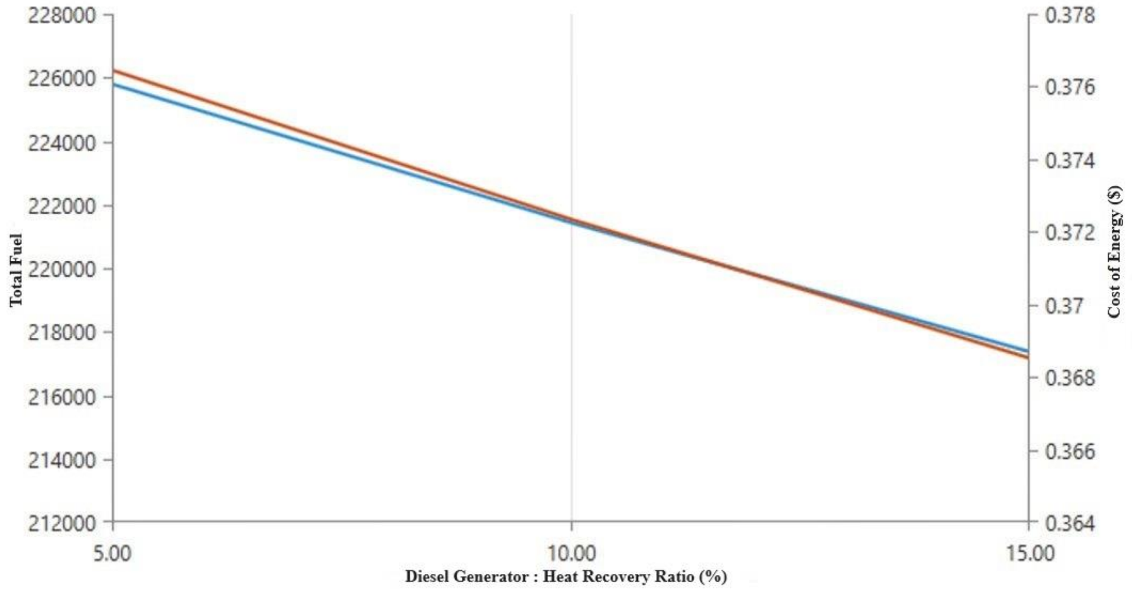

Figure 8. The impact of the generator's heat recovery rate on the unit energy cost and fuel consumption.

Impact of Solar Radiation on the solar system

The simulations conducted for the hybrid system in a region of Turkey with significant solar and wind potential demonstrate that the economic and technical parameters are optimized for local conditions. Sensitivity analyses were performed to understand potential changes if the same system were deployed in regions with higher solar radiation levels.

The analyses revealed that as the average daily solar radiation increases, solar panels operate more efficiently, producing more electricity with fewer panels. This improvement results in a reduction of the unit energy cost to as low as $0.350/kWh. Additionally, increased radiation during winter months allows the thermal load controller to utilize excess electricity more effectively, contributing more to the thermal load, reducing boiler operating times, lowering fuel consumption, and decreasing emission levels.

The analyses also indicated an increase in the renewable energy ratio within the system, reaching 43.4%. This increase signifies a reduction in the generator's efficiency, an enhancement in the solar panel's efficiency, and consequently, a reduction in the emission of harmful gases into the atmosphere. These sensitivity analyses provide crucial information for adapting system designs to different climatic conditions. A more detailed examination of these results is presented in Figure 9.

By leveraging higher solar radiation levels, the system can achieve better performance, lower operational costs, and reduce environmental impact. This adaptability is essential for optimizing hybrid energy systems across various geographic and climatic regions, contributing to a more sustainable energy future.

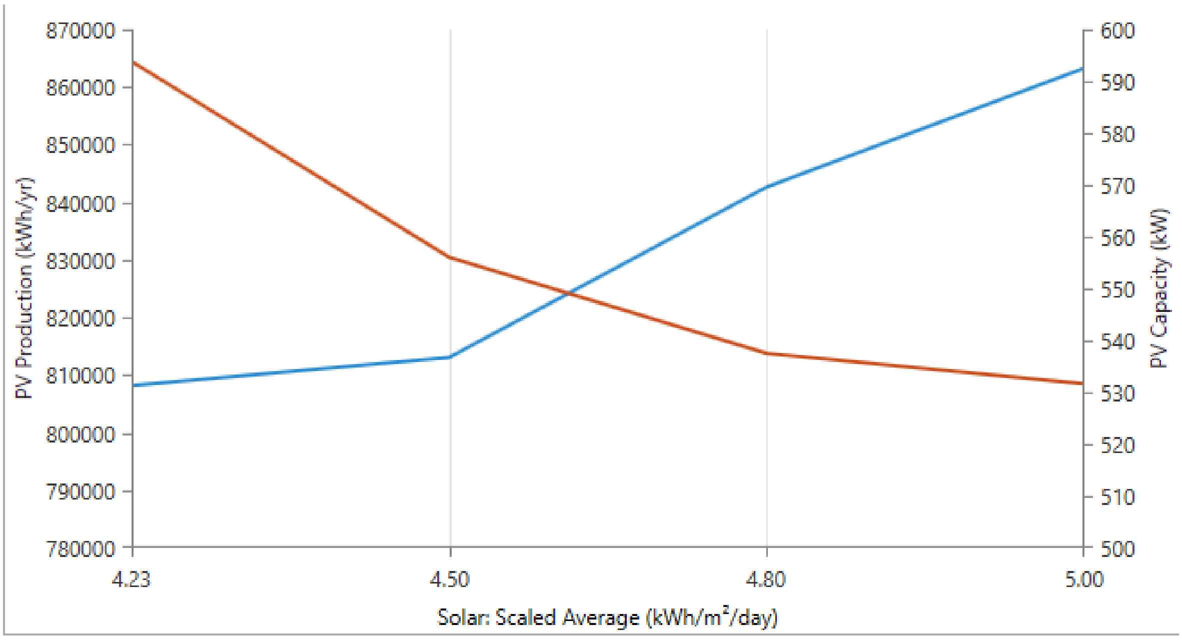

Figure 9. Impact of solar radiation on the production and capacity of PVs.

Impact of Average Wind Speed on the System

Simulations were conducted to examine the changes in system parameters if the hybrid system was installed in a region with higher wind potential. The analysis considered different average wind speeds (4 m/s, 4.85 m/s, and 5 m/s), yielding the following results:

When the average wind speed exceeds 4.85 m/s, the active use of wind turbines reduces the unit energy cost, which can increase to $0.379 under constant tower height and diesel price. The renewable energy production ratio decreases to 36.9%. Because wind speed is more consistent than solar radiation, the energy obtained from wind turbines remains more stable throughout the year. The thermal load controller can use the excess electricity from wind turbines during winter, thereby reducing the generator's electricity production and the boiler's thermal energy generation, leading to significant reductions in the emission rates.

These analyses indicate that optimizing the system based on wind energy potential can increase the unit energy cost and decrease the renewable energy ratio. The impact of wind speed and tower height on the proposed system and the energy cost change are shown in Figure 10.

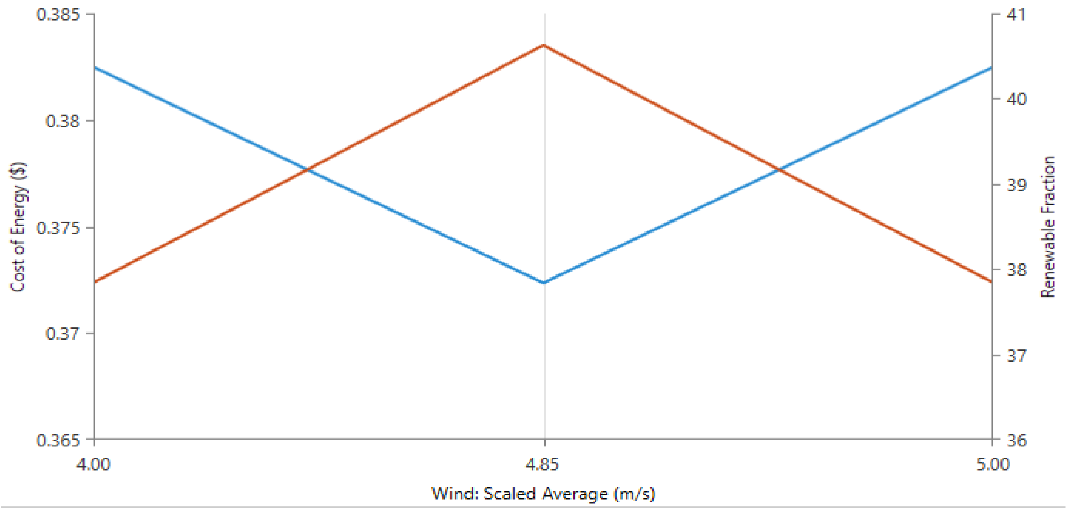

Figure 10. Impact of wind speed on energy cost and renewable fraction.

Figure 10 illustrates the relationship between the average wind speed (m/s) and the cost of energy ($) and the renewable fraction (%). As the wind speed increases, the cost of energy initially decreases but then increases slightly, whereas the renewable fraction follows an inverse trend. This indicates the complex interplay between wind turbine efficiency, energy cost, and the proportion of renewable energy in the system.

Evaluation of All Optimization and Sensitivity Analyses

The optimization and sensitivity analyses determined the necessary characteristics for the system to operate at maximum efficiency as follows:

1. Effective Use of Batteries: Efficient battery utilization ensures that energy storage systems operate effectively. This allows energy generated from solar panels or other renewable sources to be stored and used when needed.
2. Operating the Generator at a Minimum of 75% Capacity: Running the generator at a minimum of 75% capacity ensures continuous and efficient electricity production. This contributes to the generator's efficiency and helps to maintain a low unit energy cost.
3. Utilization of generator waste heat: The waste heat from the generator provides a form of cogeneration, enhancing energy efficiency. This involves using waste heat to meet thermal load requirements, thereby reducing energy costs.
4. Use of Thermal Load Controller (TLC): The TLC connects the electrical load system to the thermal load system. This ensures that excess energy is utilized by the thermal load, thereby preventing energy waste.
5. Meeting Heating Needs with a Boiler System: The boiler system meets the thermal load requirements. This allows the system to address both electricity and heating needs.

When all these parameters are integrated into the system, the unit energy cost can be reduced to $0.327. A significant portion of electricity generation is provided by solar panels, and the effective use of generator waste heat and thermal load controllers enhances system efficiency while reducing environmental impacts.

During the summer months, the system relies heavily on solar panels for electricity generation, indicating that generators are used minimally during these periods. Excess electricity produced in summer can be stored in batteries or used directly.

It is observed that fuel consumption is higher during winter. This suggests that during periods when solar panel production is lower and thermal load demand is higher, the generator and boiler are used more frequently.

The annual fuel consumption is illustrated in Figures 11 and 12. These figures show the monthly fuel consumption, highlighting how it changes according to the system’s energy demand. This information is crucial for effective energy management and system optimization.

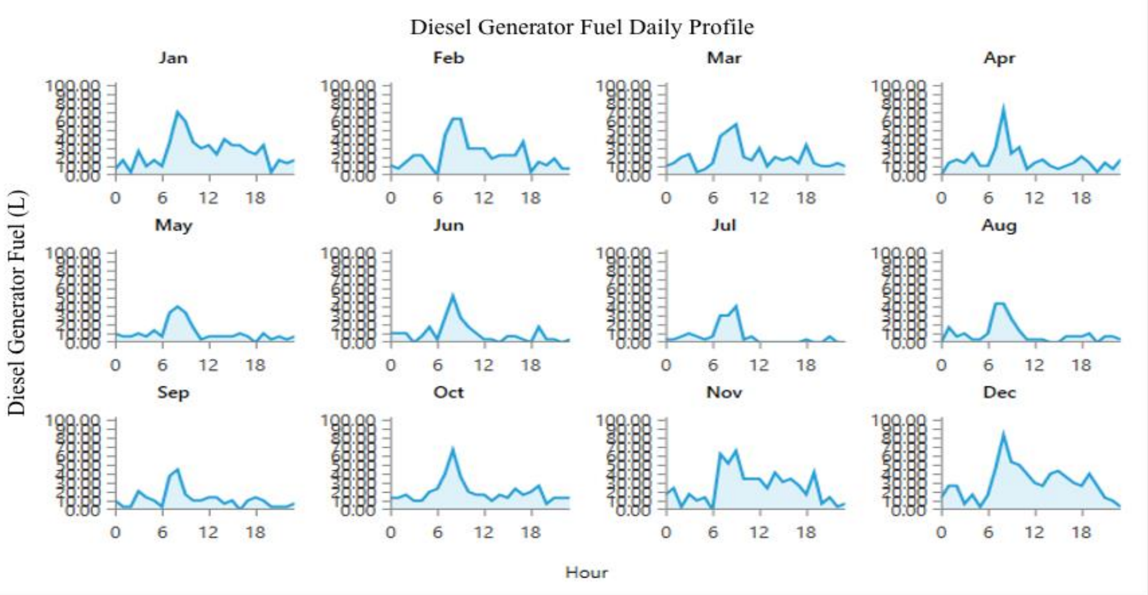

Figure 11. Diesel generator fuel daily profile.

This set of graphs shows the daily fuel consumption of the diesel generator for each month. This shows variations in fuel usage throughout the day and across different months, indicating higher consumption during winter months.

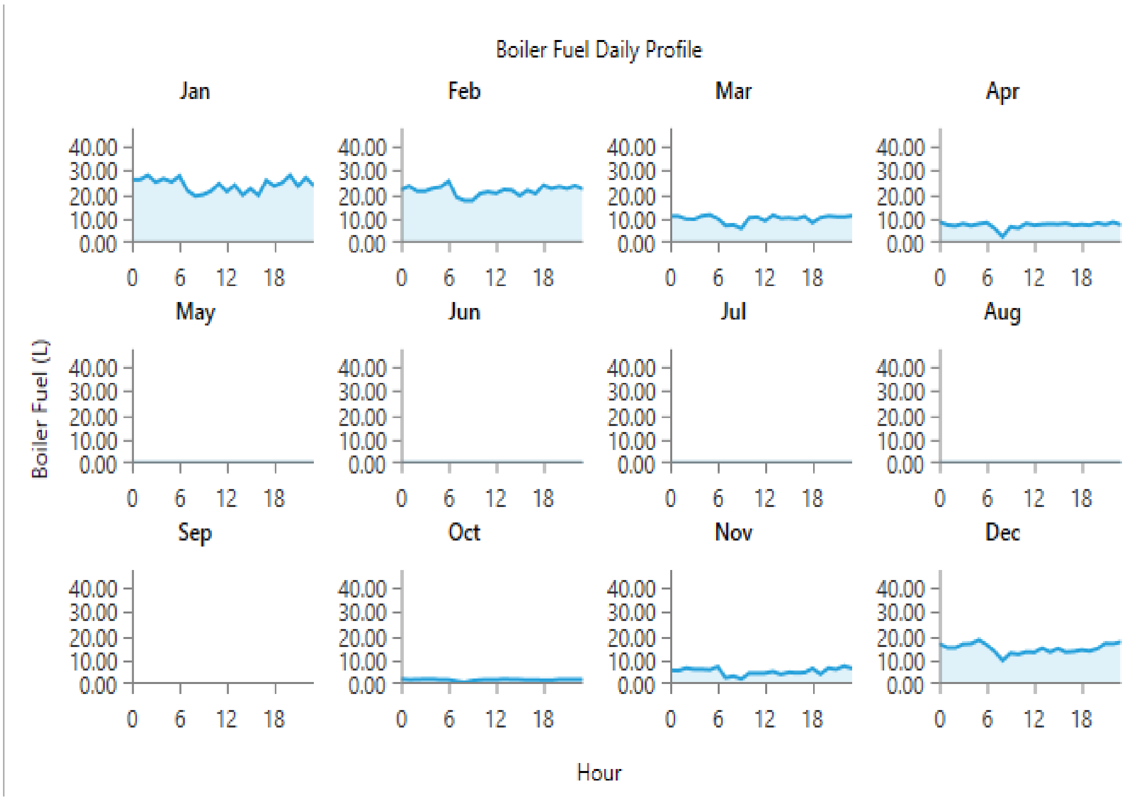

Figure 12. Boiler fuel daily profile.

This set of graphs illustrates the daily fuel consumption of the boiler for each month. The data reveal that boilers are used more during winter months, reflecting the increased thermal load demand during these periods.

By analyzing these figures, one can understand the system's fuel consumption patterns and identify opportunities for optimization and efficiency improvements.

The graph in Figure 13 illustrates how the unit energy cost of the system is affected by variations in average solar radiation and wind speed across Turkey. The analysis results indicate the following:

- Wind Speed: In regions where the wind speed reaches 5 m/s, the unit energy cost increases to \$0.379/kWh due to the use of wind turbines. This suggests that adding wind turbines in areas with moderate wind speeds does not necessarily reduce costs but can, in fact, increase them.
- Solar Radiation: In regions where solar radiation levels reach 5 kWh/m²/day, the unit energy cost decreases to \$0.350/kWh. This highlights the efficiency of solar panels in high-radiation areas, leading to lower energy costs.

These results demonstrate that the varying solar and wind conditions across different geographic regions in Turkey can significantly impact energy costs. This highlights the need for an optimal system design that is tailored to these local conditions. The analysis shows that contrary to expectations, integrating wind turbines in regions with not significantly high wind speeds can increase the cost rather than decrease it.

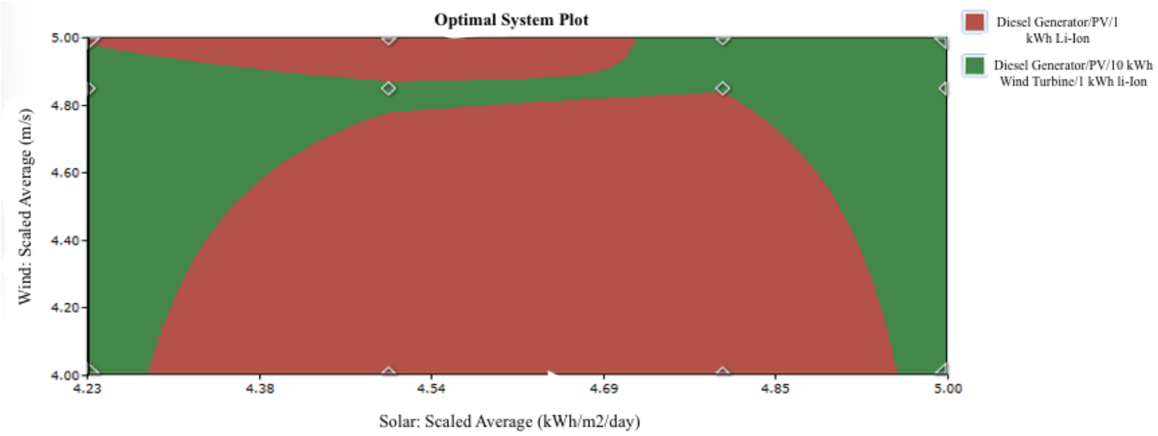

Figure 13. Optimal system type based on solar radiation and wind speed.

This graph illustrates the optimal system configuration for varying average solar radiation (kWh/m²/day) and wind speed (m/s) in Turkey. Regions with higher solar radiation benefit more from photovoltaic (PV) systems, resulting in lower energy costs, whereas regions with moderate wind speeds do not significantly benefit from adding wind turbines, potentially increasing the unit energy cost.

ConcluSION

This study analyzes hybrid systems capable of operating independently from the grid using the HOMER Pro program in regions where the electrical grid is either inaccessible or unreliable. The key findings of the analysis are as follows:

- Effective Use of Batteries in Hybrid Systems: This analysis determined the necessity of effectively utilizing batteries in hybrid systems. Efficient energy storage management allows the system to meet the electricity demand by storing energy produced from solar or wind sources for later use.
- Utilization of Generator Waste Heat: Reclaiming waste heat from generators positively contributes to system efficiency and energy costs. By using this waste heat to meet thermal loads, the system can benefit from energy savings and emission reductions.
- Cost Analysis: The system's installation cost was \$2,303,319.44, with operational costs of \$415,969.60 and a total net present cost of \$10,358,090.00. The unit energy cost was found to decrease to \$0.327/kWh, indicating that hybrid energy systems can achieve more economical energy prices than individual investments.

The results of the analysis suggest that hybrid systems can meet both electricity and heating needs more cost effectively over a 25-year period. This study demonstrates that hybrid energy systems that integrate renewable energy sources and energy storage systems offer economic and environmental benefits in off-grid areas. With technological advancements, the adoption of such systems is expected to become more widespread, and costs will decrease.

These findings highlight the potential of hybrid energy systems to provide sustainable and efficient solutions for energy production in remote and off-grid locations. By leveraging renewable energy sources and optimizing energy storage and waste heat recovery, these systems can play a crucial role in reducing the dependency on fossil fuels, lowering emissions, and promoting a greener future.

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