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Araştırma Makalesi / Research Article

Investigating the Effects of Different Types of Battery Impacts in Energy Storage Systems on Standalone Hybrid Renewable Energy Systems

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Abstract

Energy plays an important role in the development of a country. Developing countries tend to lean towards the use of domestic renewable energy sources to reduce their dependency on foreign energy. However, when looking at the world as a whole, the share of fossil fuels in energy production is at high levels. Due to the rapid depletion of fossil fuels and their increasing costs, as well as the environmental damage they cause, electricity generation from cheaper and cleaner renewable energy sources is being targeted in the area where work will be done. Hybrid energy systems are used in conjunction with backup Unitss due to the variable nature of renewable energy sources such as wind and solar. In this study, a hybrid energy system with solar-wind-diesel generator-battery components was designed through HOMERPro software to meet the electricity demand of the closed prison in Burhaniye district of Balikesir. Simulations were carried out by applying 5 different battery scenarios in the hybrid energy system, and the optimum result was obtained. As a result, the effect of the batteries used on the system was examined, and the vanadium redox battery system with a high renewable energy ratio and the lowest Units energy cost was determined to be the most optimum.

Keywords: Hybrid energy systems, Renewable energy sources, Energy optimization, Techno-economic analysis, Vanadium redox battery.

Farklı Tip Batarya Etkilerinin Şebekeden Bağımsız Hibrit Yenilenebilir Enerji Sistemleri Üzerindeki Etkilerinin İncelenmesi

Öz

Enerji bir ülkenin gelişiminde önemli bir rol oynamaktadır. Gelişmekte olan ülkeler enerjide dışa bağımlılığını azaltmak için yerli yenilenebilir enerji kaynakları kullanımına doğru eğilim göstermektedir. Fakat tüm dünyaya bakıldığında fosil yakıtların enerji üretimindeki payı yüksek seviyelerdedir. Fosil yakıtların hızla tükenmesiyle birlikte maliyetlerinin artması ve çevreye verdikleri zararlardan dolayı çalışma yapılacak bölgede daha ucuz ve temiz olan yenilenebilir enerji kaynaklarından elektrik enerjisi üretimi hedeflenmiştir. Yenilenebilir enerji kaynaklarının (rüzgâr ve güneş) değişken yapısından dolayı hibrit enerji sistemleri yedekleme üniteleriyle birlikte kullanılmaktadır. Bu çalışmada, Balıkesir'in Burhaniye ilçesinde bulunan kapalı cezaevinin elektrik yük talebini karşılamak amacıyla güneş-rüzgâr-dizel jeneratör-batarya bileşenlerine sahip hibrit enerji sistemi tasarlanmış ve tasarım aşamaları HOMERPro yazılım aracılığı ile gerçekleştirilmiştir. Hibrit enerji sisteminde, 5 farklı batarya senaryoları uygulanarak simülasyonlar gerçeklenmiş ve en optimum sonuç elde edilmiştir. Sonuç olarak kullanılan bataryaların sistem üzerindeki etkisi incelenmiş, yenilenebilir enerji oranı yüksek ve en düşük birim enerji maliyetli vanadyum redoks bataryalı sistem olmuştur.

Anahtar Kelimeler: Hibrit enerji sistemleri, Yenilenebilir enerji kaynakları, Enerji optimizasyonu, Tekno-ekonomik analiz, Vanadyum redoks batarya.

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1. Introduction

Energy is one of the most important factors that determine people's lifestyle and quality of life. It greatly influences the economy and is an essential requirement for the prosperity and comfort of countries. As the world's population increases, so does the need for energy (Güven and Hatipoğlu, 2022). Academic and industrial research on energy consumption, driven by technological advancements, focuses primarily on the efficient use of energy. Energy conservation involves the efficient operation of devices, resulting in less energy consumption to perform their functions. Efficient utilization of energy types and sources, along with reducing energy costs and ensuring uninterrupted access to energy for people, make energy management essential (Güven et al., 2022).

It is known that people have been using fossil fuels for their energy needs for many years. The environmental damage, global warming, and limited energy source of fossil fuels have led to the search for new sources. Developing countries have started to turn to renewable energy sources to reduce their external energy dependency. Renewable energy sources are more usable than fossil fuels because they are environmentally friendly and have unlimited resources (Güven and Samy, 2022). The utilization rate of primary renewable energy sources varies from country to country in the world. As a result of research, solar energy, which has a significant development, provides more significant advantages than other sources (Güven and Mete, 2022). Our country has high advantages in terms of benefiting from solar energy due to its geographical location. It is known that our country's solar energy potential is higher than many European countries (Güven, 2017). However, it is seen that solar energy is not utilized enough. In addition to solar energy, benefiting from wind energy is also among our country's potentials. The fact that solar energy is only available during the day and the energy obtained from wind energy is not continuous limits the use of these systems separately. Hybrid renewable energy systems (HRES) are called systems that use solar energy and wind energy together. HRES is also used to eliminate the disadvantages of energy sources that are insufficient where energy demand exists. Furthermore, research indicates that diesel generators are commonly employed as alternative energy sources, particularly in the event of power failures. Diesel generators are preferred, especially when energy demand is not met by natural energy sources. In particular, in places where solar energy potential is high, it is seen that diesel generators are used as an alternative backup system in HRESs established for the distribution of electrical energy during grid outage moments. In many countries, the integration of energy storage systems (ESSs) with renewable energy systems and the development of renewable energy microgrids increase the percentage of HRES and renewable energy use.

Many studies have shown that batteries have significant effects on energy balancing, power quality, power control, backup power, and increased power supply in hybrid renewable energy systems. Additionally, the use of batteries helps to reduce the time gap between electricity generation from renewable energy sources and consumption. Research on the effects of batteries in hybrid renewable energy systems also addresses issues such as battery technology selection, capacity management, battery life, battery cost, and battery disposal. While some researchers indicate that vanadium redox batteries are effective in renewable energy systems, others argue that lithium-ion batteries are more cost-effective and have higher energy density. In the past, lead-acid batteries have been used for a long time in electricity applications, but lithium-ion batteries have become increasingly popular in recent years. This is because they have a higher energy density, meaning they can store more energy in less space. Additionally, lithium-ion batteries require low maintenance and have higher safety features. Vanadium redox batteries are a technology commonly used for storing energy from renewable and environmentally friendly sources. These batteries use different ion forms of vanadium in a rechargeable electrolyte solution to increase energy storage capacity. Zinc-bromine batteries, or ZBF, are used in many applications due to their high energy density and low maintenance requirements. These batteries produce energy from a chemical reaction between zinc and bromine in an electrolyte solution. Ni-Cad batteries are long-lasting, lightweight, and reliable. However, they are harmful to the environment because they contain toxic metals such as nickel and cadmium. Sodium-sulfur batteries are used particularly in large-scale energy storage applications. These batteries work at high temperatures and produce energy from a chemical reaction between sodium and sulfur in an electrolyte solution.

In conclusion, the effects of batteries in hybrid renewable energy systems play an important role in many areas such as energy balancing, power quality, power control, backup power, increased power supply, and reducing time gaps. Therefore, batteries should be taken into consideration in the design of hybrid renewable energy systems.

In this study, unlike other studies in the literature, 5 different battery technologies, including lead-acid battery (LA), lithium-ion battery (LI), vanadium redox battery (VR), nickel-iron battery (NI) and zinc-bromine flow battery (ZBF), were used and compared on HRES. Balıkesir province was chosen as the application area, and the load demand was met without interruption from renewable energy sources. HOMERPro software was used in the system modeling and design process. Different scenarios were created during the simulation process to achieve the most optimal results. The effects of HRES were examined in all scenarios used in the study. As a result, the most suitable system was chosen in terms of economy, efficiency, and environment. Thanks to the developed models, the most efficient and cost-effective system design has been proposed for the region where the hybrid system will be implemented. Sensitivity analyses were conducted to obtain the most feasible components and battery options of the system under possible conditions.

In the literature, it has been observed that many researchers have used different hybrid components and different batteries. Table 1 presents an extensive overview of different hybrid system setups that employ a variety of battery technologies.

Table 1. Literature studies on battery effects in hybrid energy systems.

Hybrid components	Findings	Country	References
Solar panel /Battery	This study, the effect of batteries on the system performance and the life cycle costs of batteries were examined. The focus was on lead-acid batteries, and two different types of lead-acid batteries with specific characteristics were tested in the project. It was revealed that more battery life tests and an adequate number of similar tests need to be performed for specific battery types. Additionally, it was shown that longer-lasting lead-acid battery models need to be developed and validated.	Canada	(Bindner et al., 2005)
Solar Panel / Diesel Generator / Battery	This study presents a battery-backed PV-diesel hybrid power system for a village powered by solar panels, a diesel generator, and batteries. Field measurements were taken using four different generators. It was found that with increasing fuel prices, the diesel-only system became less economical compared to the others and was no longer cost-effective. It was recommended to use a demonstration hybrid power system with a 20% solar PV penetration.	Suudi Arabistan	(Rehman and Hadhrami, 2010)
Solar panel/Diesel generator/Battery	In this study, a small hybrid system in the Zaragoza province of Spain has been analyzed. A new load management strategy has been investigated to utilize renewable energy in the most optimal way. The strategy has improved the use of wind energy by shifting controllable loads to wind power.	Spain	(Lujano-Rojas et al., 2012)
Solar panel/Diesel generator/Battery	In this study, the techno-economic feasibility of a photovoltaic-diesel generator-battery hybrid energy system has been examined. Various scenarios have been studied for photovoltaic penetration ranging from 0% to 100% for an energy system (HES) for electrification. The analysis of power systems has shown that economically, the optimum configuration is a 25% photovoltaic-diesel generator-battery hybrid energy system compared to other systems.	Algeria	(Rezzouk and Mellit, 2014)
Wind turbine/Batteries	This study proposes a hybrid energy storage system, combining superconductive magnetic energy storage with a battery to reduce short-term power cycling and high discharge currents, ultimately improving battery lifespan. A novel battery life model evaluates improvements by considering both the number of charge/discharge cycles and discharge impact ratio. The study advances previous research by demonstrating the potential to improve battery life in wind energy conversion through superconductive energy storage and introducing a new methodology to achieve this	United Kingdom	(Li et al.,2015)
Solar panel/Fuel cell/Battery	In this study, an optimization model has been developed for a PV/fuel cell/battery-based hybrid energy system to cope with increasing energy consumption in the residential sector. It has been observed that this type of hybrid energy system, designed to meet residential electricity and thermal demands	China	(Ren et al., 2016)

	while minimizing annual operating costs and CO2 emissions, is effective.		
Battery/Solar panel/Fuel cell	This research paper presents the analysis of a hybrid system consisting of a photovoltaic system, fuel cell, battery, and upstream grid. The system was evaluated with two types of loads, namely electrical and thermal loads, and the study investigated how changing loads affected energy supply strategies. The study used the IGDT approach to derive robustness and opportunity functions that could guide the system operator in selecting the right strategy. The load's uncertainty was modeled to enable the operator to make informed decisions and optimize the system's performance against possible changes in the load. A case study was also simulated to demonstrate the effectiveness of the IGDT approach.	Iran	(Nojavan et al., 2017)
Solar panel/Battery/Fuel cell	The study aimed to assess the cost-efficient management of a hybrid energy system comprising photovoltaic, battery, and fuel cell components, using a demand response program. The system utilizes a battery for storing electrical energy and a thermal energy storage tank for storing thermal energy, resulting in energy savings during off-peak periods and supplying power during peak hours, leading to a reduction in overall costs. To solve the low-cost operation problem, a mixed-integer linear program has been developed.	Iran	(Majidi et al., 2017)
Solar panel/Diesel generator/Battery	This article aims to optimize rural electrification in the remote Sahara region of Algeria, where diesel generators are predominantly used. A sensitivity analysis has been conducted on an autonomous hybrid solar panel, diesel generator, and battery system. The Particle Swarm Optimization (PSO) and ε-constraint methods were utilized to minimize the total system cost. An independent hybrid PV-string-battery system was effectively installed as a reliable solution for rural areas. It has been observed that the optimum system design meets 100% of the load demand.	Algeria	(Fodhil et al., 2017)
Solar Panel/Super Capacitor/Battery	This study aimed to improve the service life of lead-acid batteries in independent photovoltaic power systems by reducing the stress on the battery, which increases operating costs due to the short cycling life of the batteries. The effectiveness of various methods to reduce battery stress was investigated and compared through theoretical analysis and numerical simulations conducted using MATLAB Simulink	Malaysia	(Jing et al., 2018)
Wind Turbine/Solar panel/Diesel generator/Battery	In this study, a hybrid energy system consisting of wind, solar, diesel generator, battery, and reverse osmosis was analyzed. The modeling of each component was carried out and explained in detail. Various algorithms were used to solve the energy management of the hybrid energy system. Optimal system design and minimizing the total cost of the system were the main objectives of the study, along with the use of software tools.	China	(Zhang et al., 2020)
Solar panel/Diesel generator/Battery	In this study, a hybrid energy system design was made using solar panels, diesel generator, and batteries for a rural area in Iraq. Three different control strategies, LF, CC, and CD, were proposed in the study. According to the project results obtained using HOMER software, the most suitable system was determined to be a 19.4 kW solar panel, a 21 kW diesel generator, a 220 battery combination, and an 8.05 kW power converter with the CD strategy.	Iraq	(Aziz et al., 2020)

2. Materials and Methods

The hybrid energy system was designed, component selection and sizing, as well as battery technology assessment were done using the HOMER Pro® software. The current system design was based on input load data, technical specifications, and financial characteristics of various components. The aim was to achieve the optimal system response with the least Net Present Cost (NPC) and Cost of Energy (COE) for the location using different battery technologies. The research objective was to obtain an optimal solar/wind/diesel generator/battery system design for a location prone to frequent power outages. To simplify and enhance the planning and utilization of these systems, a three-step methodological framework was assessed, consisting of a comprehensive (1) initial assessment, (2) design optimization study, and (3) results, as illustrated in Figure 1. During the first stage, pre-optimization analysis was carried out to comprehensively study the estimated local demand for load as well as the available renewable energy sources, subject to constraints related to available energy sources and meteorological properties. Following the initial stage, system designers analyzed the optimal mix of applicable energy technologies to maintain a balanced load demand. The HOMER Pro® program was used to appropriately model and analyze the selected energy technologies in the context of five different battery technologies. The aim was to minimize net present cost, energy cost, and pollution while meeting electrical load demand. The third stage involved reviewing the least expensive and most environmentally friendly system with the best reliability level, which was evaluated based on numerous operational, financial, and environmental criteria.

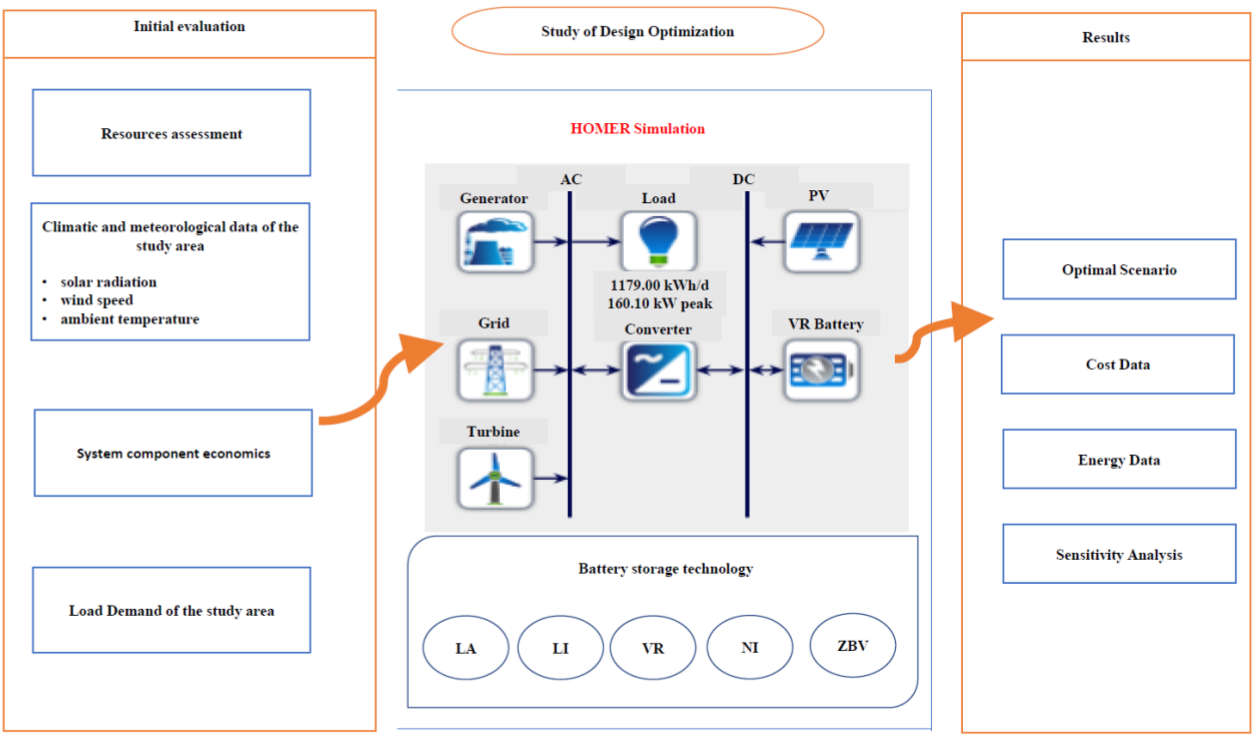


Figure 1. Schematic representation of study techniques (Barakat et al., 2022).

2.1. Introduction to the Study Area

The study area is a prison located in Burhaniye district of Balıkesir. A hybrid energy system consisting of solar and wind energy sources independent from the grid has been evaluated to meet the energy demand of the prison, which accommodates 1200 people. The meteorological data used in the study was provided by the Turkish State Meteorological Service. Hourly solar radiation, wind speed, ambient temperature, and load data from annual records were used to create a profile of the study area. Figure 2 shows the hourly resolved solar radiation profile over one year (8760 hours), Figure 3 shows the monthly profiles of wind speed at a height of 10 m above the ground, and Figure 4 shows the monthly profiles of ambient temperature as a time series graph. As seen in Figure 2, the solar energy potential of the study area is higher in the summer months compared to the winter months. Wind turbines will serve as complementary energy sources when solar energy may be insufficient during the winter months, complementing each other with solar energy. These are the two most preferred energy sources in hybrid systems. The average daily energy consumption in this prison was 1179.0 kWh/day with a random fluctuation of 15.092%. The maximum and minimum average loads per hour throughout the year were 160.1 kW and 49.13 kW, respectively. The annual, daily, and seasonal load demand profiles are also shown in Figure 5. For the purpose of economic analysis, a nominal discount rate of 20% and an inflation rate of 17% were taken into account. The project life of the Hybrid Renewable Energy System (HRES) was chosen as 25 years.

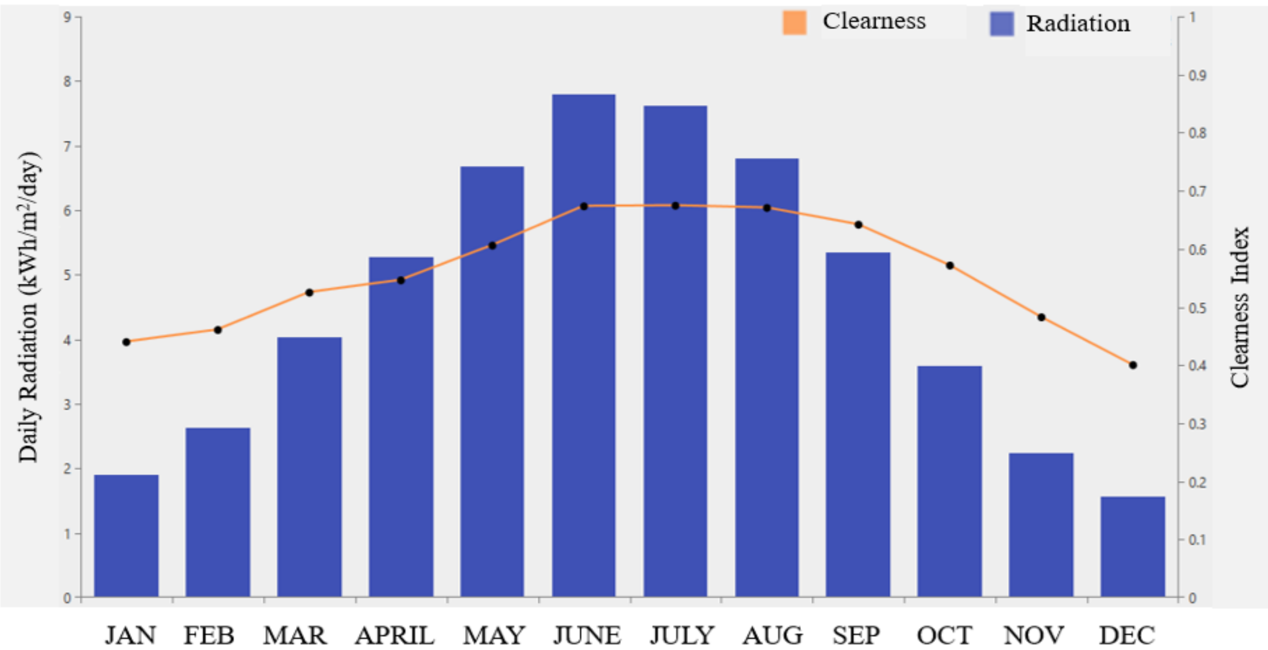


Figure 2. The radiation profile of the study area.

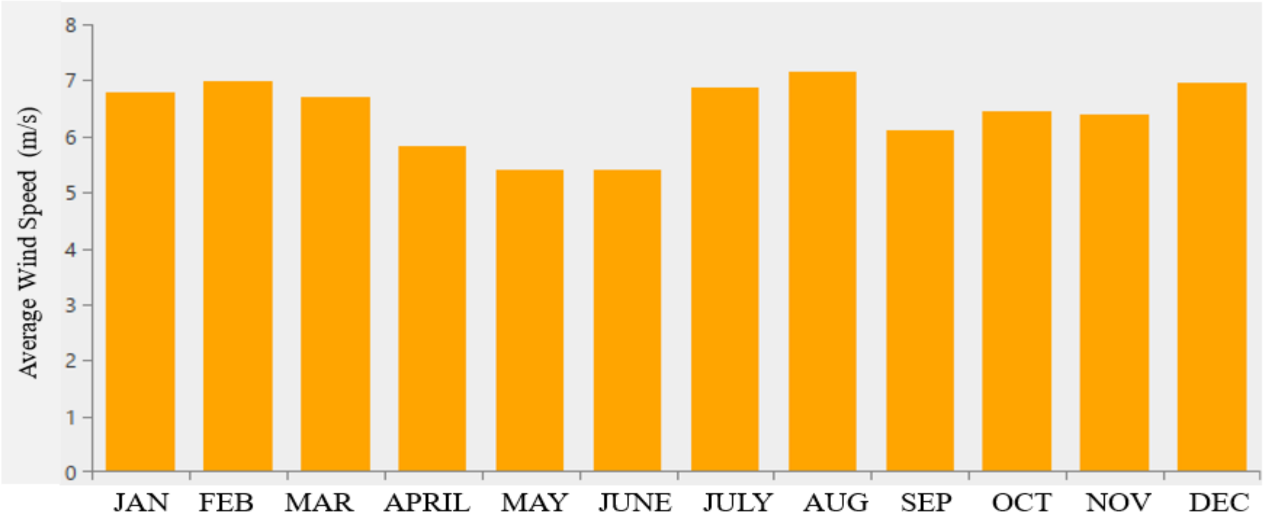


Figure 3. The wind speed of the study area.

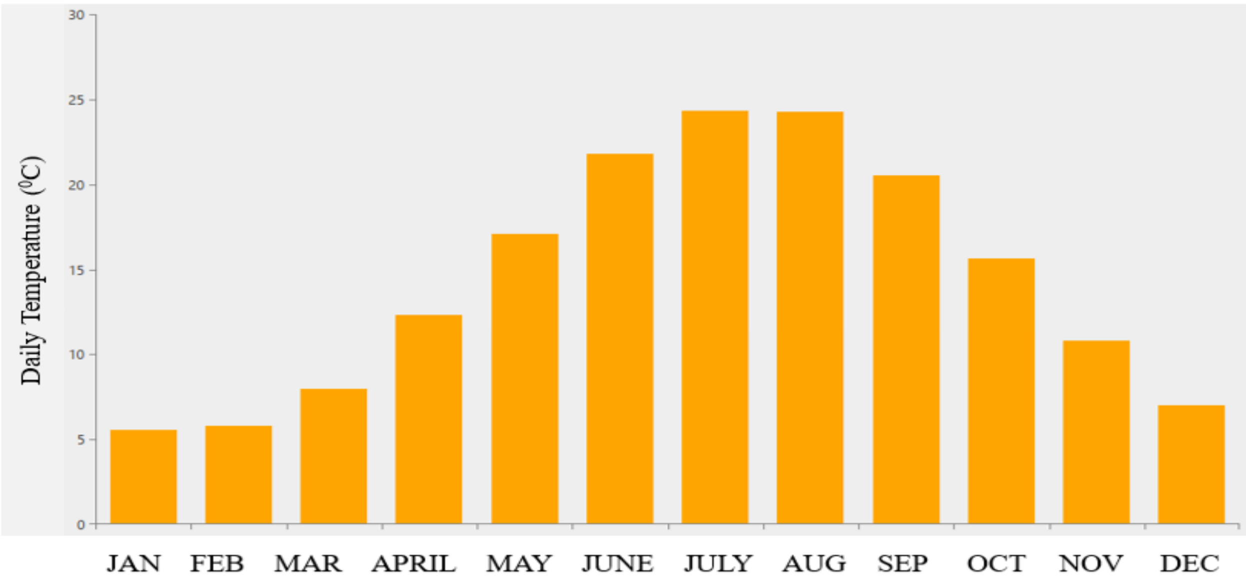


Figure 4. The Ambient temperature of the study area.

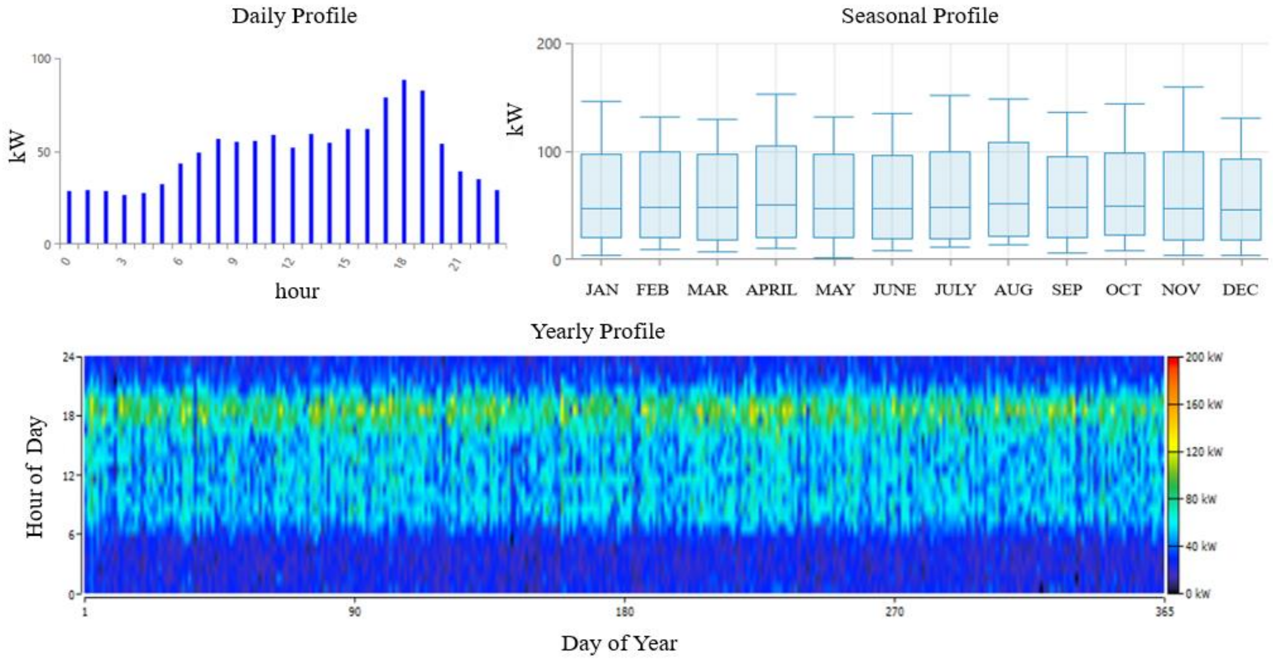


Figure 5. Load profile of study area.

2.2. Component Modeling for Energy Systems Analysis

The HOMERPro simulation program, developed by the National Renewable Energy Laboratory, is the go-to tool for analyzing hybrid power systems. This simulation program incorporates data on resources, technical and economic factors of system components, load data, and other relevant project quantities as inputs. Through HOMER simulation, researchers can evaluate the performance of hybrid power systems under various conditions and identify optimal system designs based on factors such as cost, reliability, and sustainability. The biggest benefit of the HOMER software is designing the long-term operation of a system. Many hybrid energy systems with different combinations that cover renewable energy sources determined by the user can be easily modeled with the HOMER program. Additionally, this program is a program that provides optimal budgeted systems through the design of micro power systems and different combinations of power suppliers. HOMER, the world's most advanced microgrid modeling software, uses the total of operating and installation costs for the combination of lifespan and Units energy costs as the physical behavior of the system . The diagram in Figure 6 depicts a hybrid power system that is not dependent on the grid. The system comprises a photovoltaic (PV) array, wind turbine, bidirectional converter, and battery banks (LA, LI, VR, NI, and ZBV) that collectively supply power to the designated prison work area.

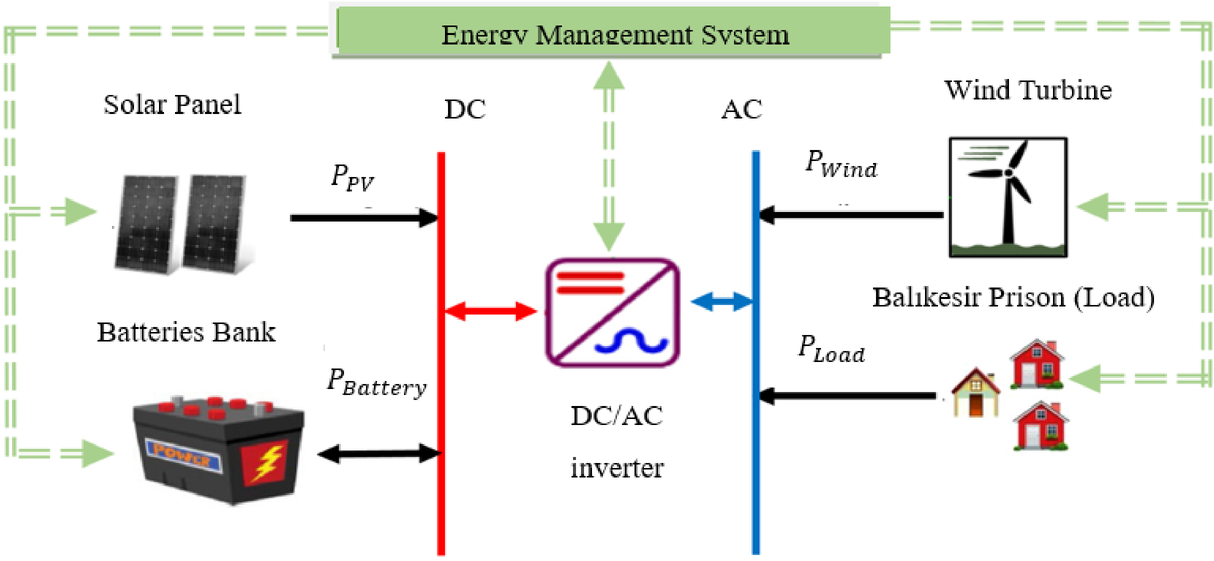


Figure 6. Proposed hybrid energy system architecture.

2.2.1. Modeling Solar Panel

One of the most important components of a hybrid system is solar panels. Solar panels are low-cost systems that do not require moving parts to generate electricity when exposed to sunlight. Due to Turkey's high solar energy potential, solar panels can be considered one of the best renewable energy sources. The electrical energy produced by the PV system can be calculated using equation (1). In the study, the solar panel cost for 1 kW is $550, the renewal cost is $550, the annual maintenance cost is $10, and the panel life is assumed to be 25 years.

$$P_{pv_{out}}(t) = P_{(PV_{rated})*} \frac{G_{(t)}}{G_{t-STC}} * [1 + \alpha_t(T_C(t) - T_{C-STC}] \quad (1)$$

$P_{pv_{out}}(t)$ represents the output power (in W) of the PV module, $G_{(t)}$ represents the solar irradiance value (in W/m^2), $P_{(PV_{rated})}$ represents the nominal power value (in W) under standard test conditions (STC), G_{t-STC} represents the solar radiation value at STC (G_{t-STC}=1000 W/m^2), α_t (-3.7x10^{-3} (1/°C)) represents the temperature coefficient, and T_{C-STC} represents the cell temperature at STC (T_{C-STC} = 25°C), while T_{amb} represents the ambient temperature (in °C). The cell temperature $T_C(t)$ is calculated using Equation (2) (Güven and Samy, 2022).

$$T_C(t) = T_{amb}(t) + [0.0256\ x\ G_t(t)] \quad (2)$$

2.2.2. Modeling Wind Turbine

Wind turbines are renewable energy sources that convert mechanical energy generated by the rotation of blades with wind speed into electrical energy. The location of the wind turbine is crucial for efficiency. In this study, the economic data for the wind turbine to be used is chosen as a cost of $500 per kW, installation and renewal costs of $500, an annual maintenance cost of $10/kW, a turbine height of 17 m, and a turbine life of 20 years. Equation (3) is used to calculate the power output of the wind turbine and is based on information such as wind speed and blade characteristics.. In contrast, Equation (4) incorporates the power law constant and the reference wind speed value at the reference height to determine the wind speed at a fixed altitude.

$$P_{WT} = \begin{cases} 0 & v(t) \leq v_{cut-in} \\ P_r \frac{v(t) - v_{cut-in}}{v_r - v_{cut-out}} & v_{cut-in} < v_r \\ P_r & v_r < v(t) < v_{cut-out} \end{cases} \tag{3}$$

The wind turbine's rated power is denoted by P_r, while $v(t)$ (measured in meters per second) stands for the wind speed at a given time. Furthermore, $v_{cut-out}$ represents the minimum wind speed at which the turbine is turned off for safety reasons, v_r denotes the wind speed at which the turbine operates at its maximum capacity, and v_{cut-in} is the minimum wind speed required for the turbine to start operating (Mokhtara et al., 2021).

$$V_2 = V_1 * \left(\frac{\mathrm{h}}{\mathrm{h_{ref}}}\right)^{\beta} \tag{4}$$

The equation (4) defines h (m) as the height of the hub of the wind turbine, $\mathrm{h_{ref}}$ (m) as the reference height (h) of the wind turbine, V_1 (m/s) as the wind speed at the hub height of the turbine, V_2 (m/s) as the wind speed at the reference height, and β as the exponent of the power law (Samy et al., 2021).

2.2.3. Modeling Battery

Batteries are electrochemical components that can store electrical energy in chemical form. They enable excess energy generated by renewable energy sources to be stored for later use. The stored energy is in the form of DC voltage that is transferred to the system. As the cost of batteries is high, the number of batteries used in a system has a significant impact. The study involved the testing of five distinct battery technologies, namely VR, LA, NI, LI, and ZBF, to identify the most suitable option for the hybrid renewable energy system (HRES). Table 2 provides significant information regarding the chosen battery technologies. Simulations were repeated by placing 5 different batteries in the scenario determined in the HOMER program. The HOMER software uses different methods such as Peukert's equation and Coulomb's law for battery modeling. It also takes into account the aging effect of the battery (Güven and Mete, 2021).

Peukert's equation calculates the actual capacity of the battery based on factors such as voltage, capacity, and discharge rate. Coulomb's law calculates the energy losses that occur during the charging and discharging processes of the battery. These two equations provide important information about the battery's performance and aging effect.

The following Equation 5 is used for battery modeling in HOMER software.

$$I(t) = E(t-1) - E(t) / \left[(K * \Delta t * \left(\frac{E(t-1)}{Q_{cap}} \right)^n) + 1 \right] \quad (5)$$

Here, I(t) represents the Battery current at time t [A], E(t-1) represents the Battery state of charge at time t-1 [Ah], E(t) represents the Battery state of charge at time t [Ah], K represents Peukert's constant, Δt represents the time step [h], Q_{cap} represents the Battery capacity [Ah], and n represents Peukert's exponent.

The Peukert equation is used to calculate the actual energy capacity of a battery, based on factors such as discharge rate and Peukert's constant. Battery capacity can be estimated under different load conditions using the Peukert equation

Table 2. Characteristics of the battery types used in the study.

Parameters	LA	LI	VR	NI	ZBF
Rated voltage(V)	2	51.2	48	1.2	48
Max. charge capacity (Amper hour)	3570	328	417	1000	215
Rated energy capacity (kWh)	715	16.8	20	1.2	10.3
Max. charge current (A)	610	263	105	500	52.1
Max. discharge current (A)	610	328	105	500	104
Round-trip efficiency (%)	86	97	75	85	75
Capital cost ($)	722	15000	10700	970	8000
Cost of renewal ($)	665	13800	9300	850	7400
Maintenance and repair cost Cost ($/year)	180	1	1	1	1
Lifespan (year)	15	25	25	20	25

2.2.4. Modeling Diesel Generator

A diesel generator should be selected to meet the load demands and operate at an average level of high load. If a battery bank is installed with a diesel generator for a short period of time, it helps overcome peak load demands and thus reduces the capacity of a diesel generator. The diesel generator charges the battery through a charging device that converts AA and DA energy. The battery allows fuel consumption to be reduced by allowing the generator to operate close to its rated values. Several generators can work in parallel and meet different load levels. Integration of various renewable sources with diesel generators contributes greatly. A diesel generator adds reliability to a hybrid system. Regular maintenance and repair are always recommended to extend the life of the generator. Diesel generators are used when the battery charge drops below a certain value or when the battery and renewable energy source cannot meet the load demand. Diesel generators can be shut down if there is sufficient power from renewable sources and the battery to meet the load demand (Güven and Yörükeren, 2022).

In this study, a 180kW diesel generator is used and the cost per kW is taken as $250. The renewable cost is $250, and the hourly operating and maintenance cost is $0.030. The operating life of the diesel generator is 15,000 hours. The amount of fuel consumed per hour by the generator is 4.96 liters. Table 3 shows the fuel characteristics and emission values of the diesel generator.

Table 3. Values related to the emission and fuel properties of a diesel generator.

Emission Quantity	Value	Fuel Quantity	Value
CO (g/L Fuel)	16.5	Lover heating value (MJ/kg)	43.2
Unburned HC (g/L Fuel)	0.72	Density (kg/m^3)	820
Particulates (g/L Fuel)	0.1	Carbon content (%)	88
Fuel sulfur to PM (%)	2.2	Sulfur content (%)	0.4
NO_X (g/L Fuel)	15.5	-	-

2.2.4. Inverter Modeling

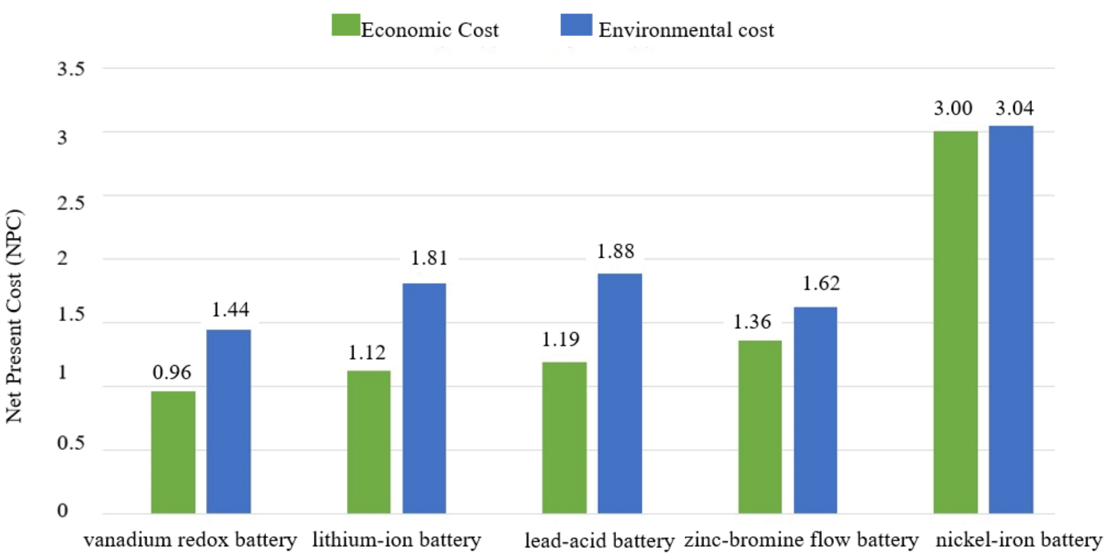
A bidirectional inverter is an essential component in a hybrid system that includes a storage system and a backup diesel generator. It can transfer power in both directions simultaneously. It can function as a rectifier circuit that converts the AA diesel generator voltage to the DA voltage and charges the battery bank. It also acts as an inverter that converts the DA voltage to the AA voltage required by the load, providing a path from the DA battery to the AA load. To meet the demands, an optimal model needs to be developed through simulation and design using HOMER software. The installation and renewal costs of the converter are $300 with a lifespan of 15 years and an efficiency of 95% (Güven and Poyraz, 2021).

3. Findings and Discussion

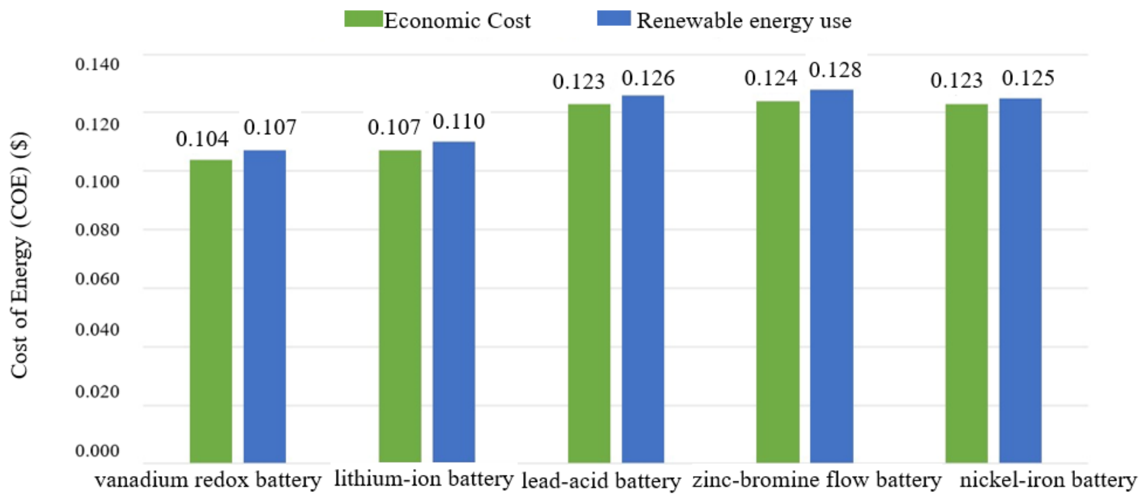
The aim of this research is to determine the most efficient and cost-effective strategy for HRES. The HOMERPro software simulates the off-grid system configuration for a prison in Balıkesir. The impact of a long lifespan on the optimal system design has been examined in detail in this article. A hybrid system consisting of wind turbines, generators, solar panels, and battery components has been applied to 5 different battery types: Lithium-ion, Lead-acid, Vanadium redox, Zinc-bromine, and Nickel-iron. Table 4 presents the results of the economic and environmental characteristics of the 5 different battery types used in the off-grid system. Figures 7 (a) and (b) show the cost analysis graphs of the batteries in the off-grid system. A battery cost analysis chart is presented in which the batteries are assessed in terms of their environmental impact, cost, and renewable energy fraction for the hybrid energy system. Here, it is seen that when a vanadium redox battery is used, the Units energy cost of HRES is 0.104 ($), and the net present cost is 963,648 ($), which is more optimal than the other 4 different batteries.

Table 3. Results of battery sizing optimization.

Battery	NPC($)	COE($)	Operating Cost($)	Initial Cost($)	Renewable Energy Fraction (%)	Solar Panel (kW)	Wind turbine (kW)	Number of batteries	Generator (kW)
Vanadium redox	963648	0.125	15456	70,965	96.6	277	224	33	180
	1.44M	0.182	9945	1.25M	100	420	271	78	-
Lithium-ion	1.12M	0.142	17236	805983	100	254	240	31	180
	1.81M	0.231	12239	1.59M	95.9	754	203	68	-
Lead-acid	1.19M	0.151	41299	434,853	96.4	256	256	118	180
	1.88M	0.239	59871	788369	100	846	501	236	-
Zinc-bromine	1.36M	0.173	14638	1.10M	96.3	255	297	91	180
	1.62M	0.206	15301	1.34M	99.1	787	393	77	180
Nickel-iron	3.00M	0.381	131509	596689	58.7	58.5	1006	10	180
	3.04M	0.386	117158	895729	66.3	508	1074	10	180



(a)

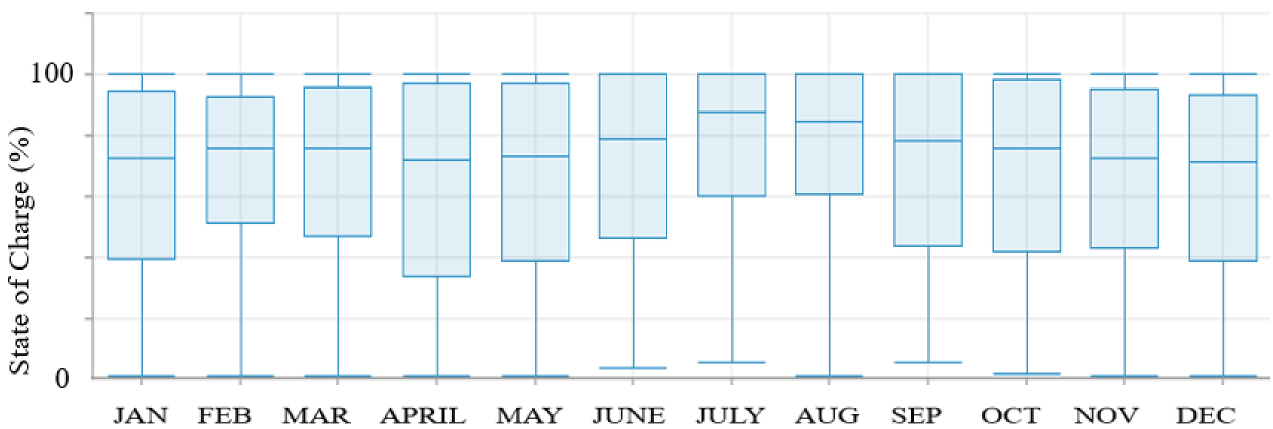


(b)

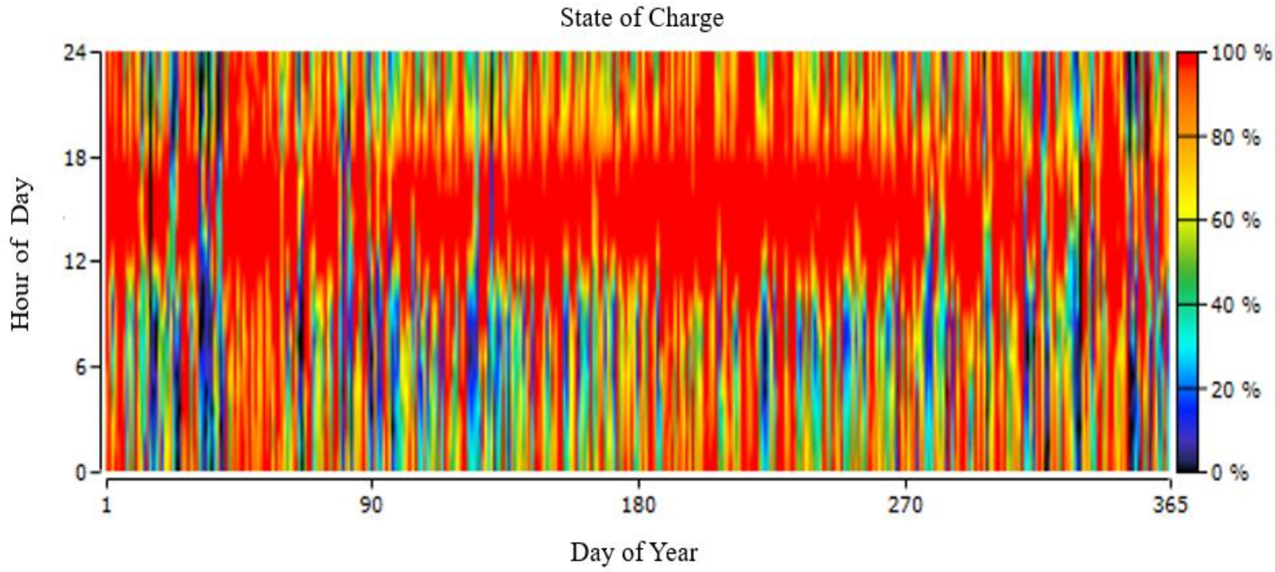
Figure 7. Cost analysis chart of the batteries (a) NPC (b) COE.

3.1. Effects of Batteries on the Analysis Results

The minimum charge level of the batteries has been set as 20% and a grid-independent system has been designed. Figure 9 shows the charge status by days of the year and by months of the year. As seen in Table 5, the annual energy input to the batteries is expected to be 136,930 kWh, the annual energy output from the batteries is expected to be 102,756 kWh, and the energy loss in the batteries is expected to be 34,241 kWs per year. High-energy storage solutions are required for larger and longer-lasting systems in hybrid energy systems. Vanadium redox batteries, also known as vanadium flow batteries, are essential components of hybrid energy systems due to their advantages such as being fully rechargeable, discharging nearly 100% of the stored energy, and lasting for more than 20 years without degradation.



(a)



(b)

Figure 8. State of charge batteries (a) monthly (b) day of year.

3.2. The Impact of Solar Panels on the System

The power output values of the solar panels used in the system selected in Figure 9 were obtained at different days and times of the year. When the data in Table 4 is examined, it is found that the PV panel capacity in the off-grid system is 277 kW. The system operates for 4,388 hours annually. It is seen that the total electricity production will be 416,928 kWh/year. The Units cost of electricity production from the panels is 0.0266$/kWh.

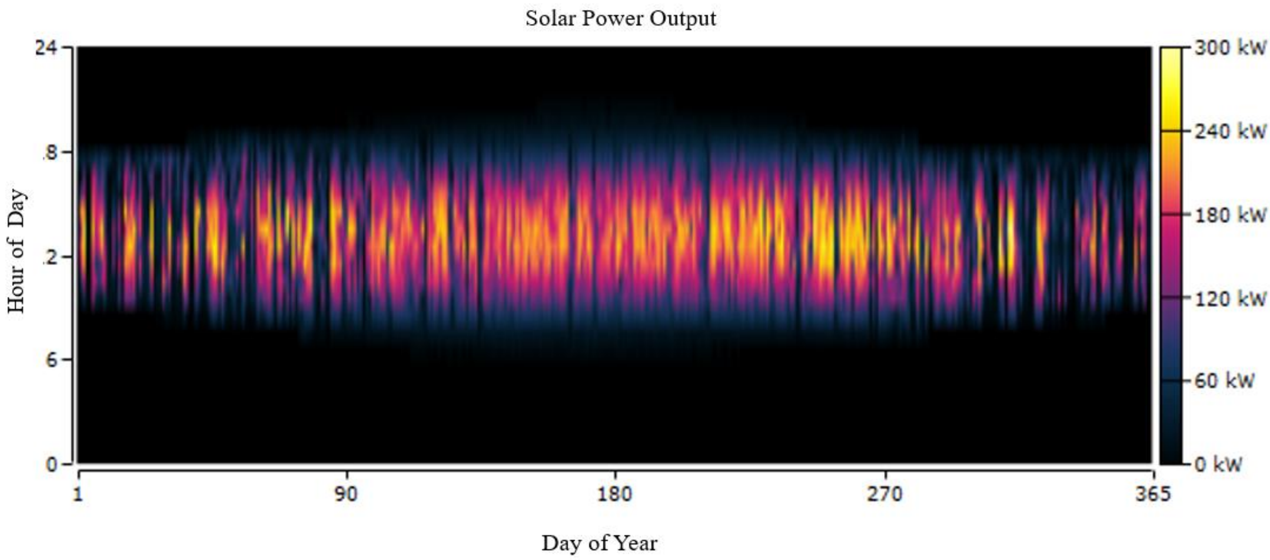


Figure 9. Output power values of solar panels in the system.

Table 4. Technical and economic Quantity of solar panels.

Quantity	Value	Units	Quantity	Value	Units
Rated capacity	277	kW	Minimum output	0	kW
Mean output	47.6	kW	Maximum output	285	kW
Mean output	1.142	kWh/g	PV penetration	96.9	%
Capacity factor	17.2	%	Hours of operation	4388	hour/year
Total production	416928	kWh/year	Levelized cost	0.0266	$/kWh

3.3. The Impact of Wind Turbines on the System

The power output graph for the wind turbines used in the system at different days and times of the year is shown in Figure 10. The output power values obtained in the graph vary according to the current wind speed of the region and the production amount required by the system. As seen in Table 5, the wind turbines used in the system operate for 7,523 hours per year and produce a total of 589,133 kWh of electricity annually. The Units cost of electricity produced by the wind turbine is found to be 0.0163$/kWh.

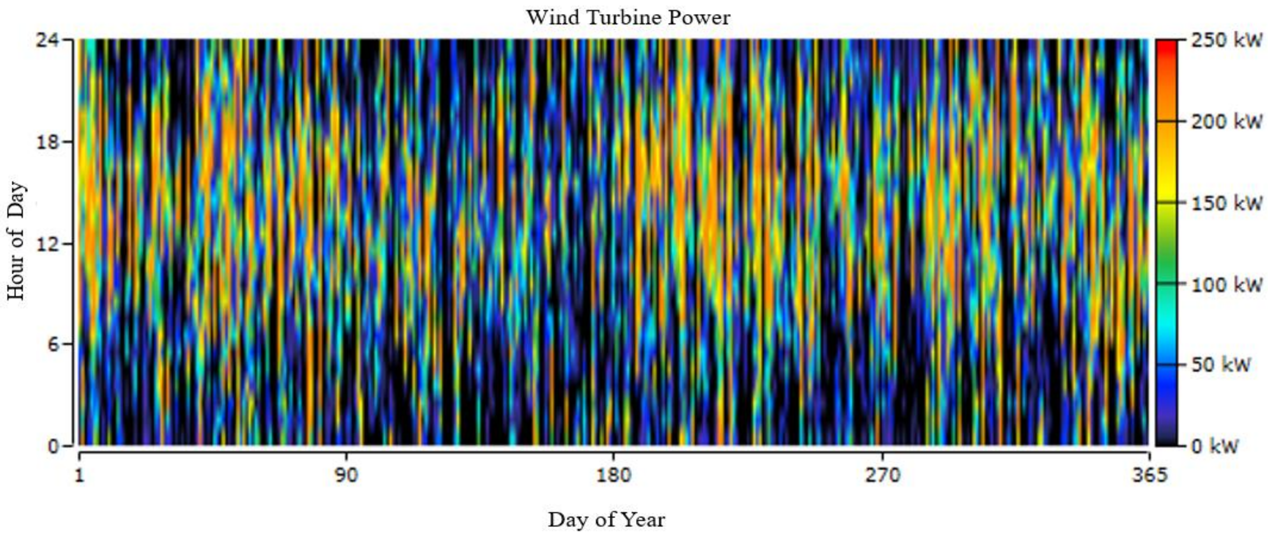


Figure 10. Output power values of wind turbine in the system.

Table 4. Technical and economic Quantity of wind turbines.

Quantity	Value	Units	Quantity	Value	Units
Total rated capacity	224	kW	Maximum output	224	kW
Mean output	67.3	kW	Wind Penetration	137	%
Capacity factor	30	%	Hours of operation	7523	hour/year
Total production	589133	kWh/year	Levelized cost	0.0163	$/kWh
Minimum output	0	kW	-	-	-

3.4. The Impact of Diesel Generator on the System

The chart in Figure 11 displays the power output of the diesel generator used in the system at various times throughout the year. Because of the high cost of fuel and its negative impact on system emissions, the diesel generator contributes very little to the total energy production. According to Table 5, the generator produces a total of 14,674 kWh/year, and the cost of the produced electricity is 0.333$/kWh. The cost of energy produced by the diesel generator is higher than that of the other system components, resulting in an increase in the Units energy cost. The generator is required to operate in the system when the wind turbines and solar panels cannot produce the required energy, and the battery levels are low. If the generator is not used, the number of batteries needed should be increased. As a result, although it is the last component to meet the system load requirement, the presence of the generator is critical.

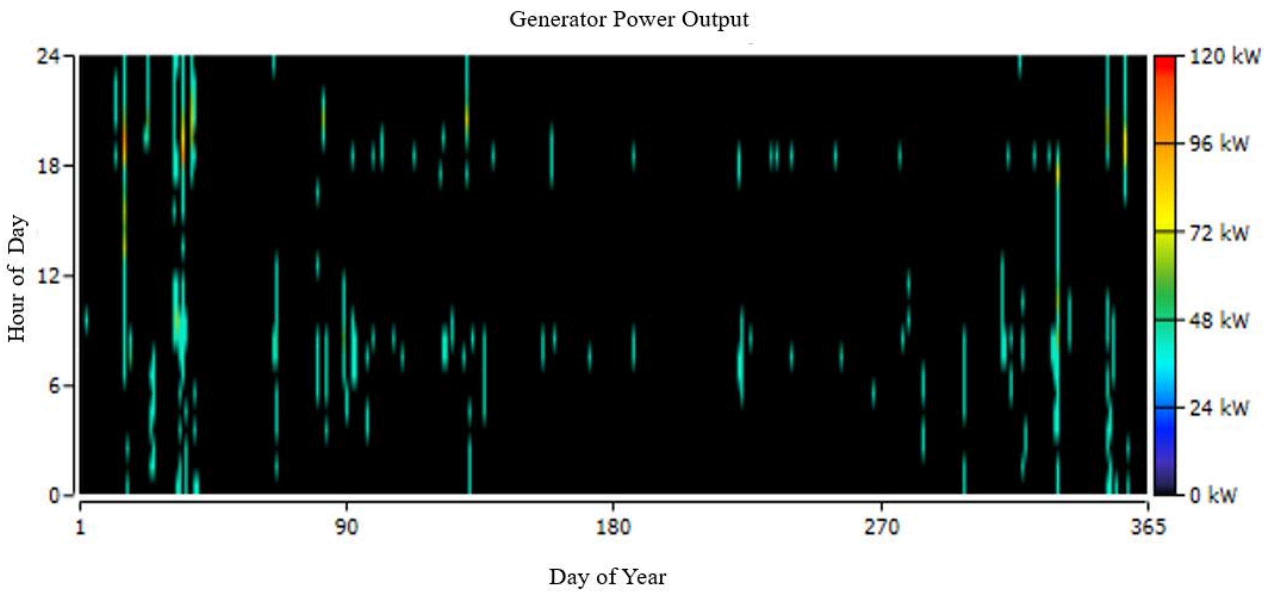


Figure 11. Output power values of generator in the system.

Table 5. Numerical data of the diesel generator.

Quantity	Value	Units	Quantity	Value	Units
Hours of Operation	310	hours /year	Mean Electrical Output	47.3	kW
Number of Starts	122	starts /year	Minimum Electrical Output	45.0	kW
Operational Life	48.4	year	Maximum Electrical Output	106	kW
Capacity Factor	0.931	%	Fuel Consumption	5001	L
Fixed Generation Cost	15.4	$ /hour	Specific Fuel Consumption	0.341	L/kWh
Marginal Generation Cost	0.333	$/kWh	Fuel Energy Input	49206	kWh /year
Electrical Production	14674	kWh /year	Mean Electrical Efficiency	29.8	%

For an autonomous system, it can be inferred from Table 6 that carbon dioxide has the highest emission rate of 13090 kg/year. Subsequently, carbon monoxide and nitrogen oxides have the next highest emission rates of 82.5 kg/year and 77.5 kg/year, respectively.

Table 6. Emission values.

Quantity	Value (kg/year)
Carbon Dioxide	13090
Carbon Monoxide	82.5
Unburned Hydrocarbons	3.60
Particulate Matter	0.500
Sulfur Dioxide	32.1
Nitrogen Oxides	77.5

The overall contribution of system components to the total production is highly significant in a hybrid energy system. The results of the analysis are presented in Figure 12, which shows the monthly electricity production data of the system components. It is apparent that the total production is fulfilled by wind turbines, solar panels, and diesel generators, contributing 57.7%, 40.8%, and 1.44%, respectively, with a 96.6% renewable energy fraction. As there are enough renewable energy resources, the diesel generator is believed to be utilized only for meeting the short-term load demand.

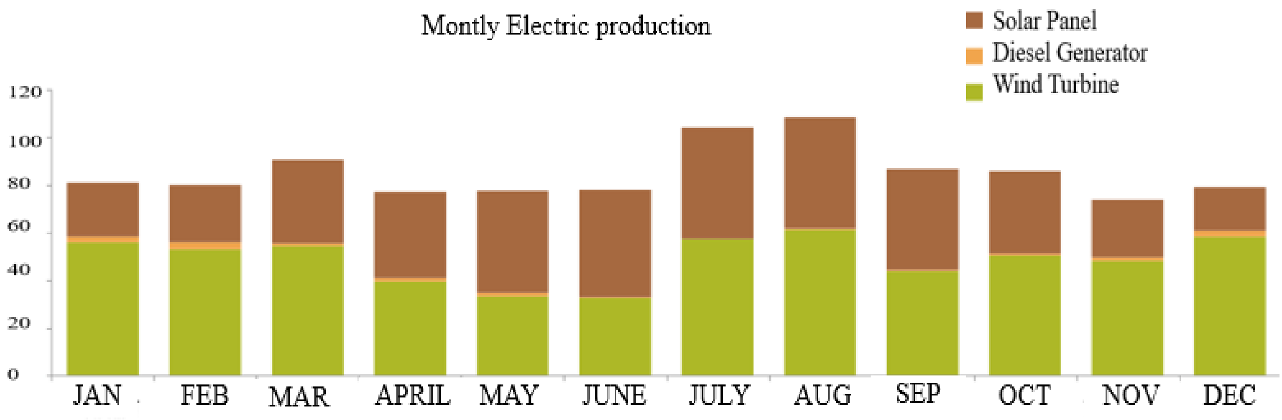


Figure 12. Monthly production graph of hybrid energy system components.

Table 7. Cost optimization results.

Component	Capital($)	Replacement Cost ($)	Maintenance Cost ($)	Fuel ($)	Salvage Cost ($)	Total ($)
Generator	45,000.00	0.00	30,617.47	128,96129	11.549,81	193,028.95
Wind Turbine	112,000.00	67,5002	40,969.61	0.00	44,606.14	172,864.49
Solar Panel	152,381.33	0.00	50,673.73	0.00	0.00	203,055.07
Vanadium Battery	353,100.00	0.00	603.57	0.00	0.00	353,703.57

Converter	38,483.70	26,32364	0.00	0.00	6,811.94	57,995.40
Total Cost	700,965.03	93,824.66	122,864.38	128,961.29	62,967.89	983,647.47

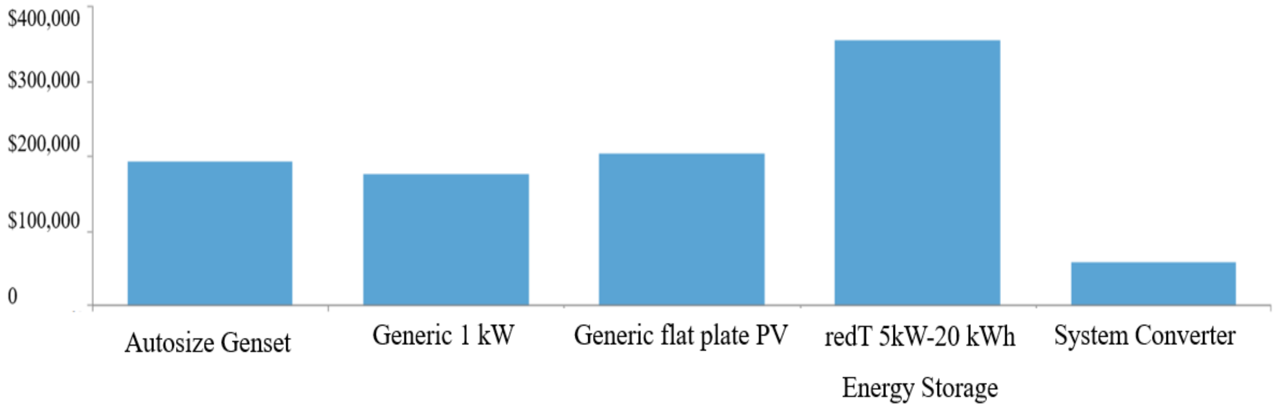


Figure 13. The cost impact profile of the components of the hybrid energy system.

After optimization, a cost analysis graph was generated to show the expenses associated with meeting the load demand in the designated operating area. Table 7 data revealed that the net present cost is $983,647.50, with an energy Units cost of $0.125/kWh and an operating cost of $15,455.57. This information is summarized in Figure 13.

4. Conclusions and Recommendations

In this study, the feasibility of applying a standalone solar/battery system with five different types of batteries to meet the electricity demand of the Burhaniye closed prison located in Balıkesir from a technical and economic perspective was investigated using HOMER Pro software. As seen in this study, detailed analysis is crucial as changes in components also result in economic changes in various system designs depending on the variation of the electricity load. Additionally, the utilization of renewable energy sources needs to be increased to reduce the reliance on fossil fuels to meet the electricity demand. Five different battery simulations were performed in this study, and the most cost-effective solution was obtained when using vanadium redox flow battery. The simulation results showed that the net present cost was $983,647.50, the Units energy cost was $0.125/kWh, and the operation cost was $15,456 when using vanadium redox flow battery. The COE values of the system were obtained as $0.231/kWh for lithium-ion, $0.239/kWh for lead-acid, $0.206/kWh for zinc-bromine, and $0.381/kWh for nickel-iron batteries.

The use of vanadium redox flow batteries in hybrid energy systems is an important step for the storage of renewable energy sources due to their high energy efficiency, long lifespan, and eco-friendly features compared to other batteries. Therefore, the development and widespread use of vanadium redox flow batteries will help make renewable energy-based energy systems more effective and sustainable.

This study aimed to lead the way for the hybrid energy systems to be established in areas with the same load profile. Since energy storage is crucial in this field, different storage components other than batteries should also be considered. The methodology employed in this study has the potential to be replicated in other case studies, and the results obtained may be applicable to areas with comparable weather conditions.

Authors' Contributions

Aykut Fatih GÜVEN: Planned the analysis and wrote the article by evaluating the results.
Şaban Türkmen: Collected the data and conducted the analysis.
Ertuğrul Aşıklı: Performed the statistical analysis of the study.
Gamze Örnek: Conducted data collection and graphic design.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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