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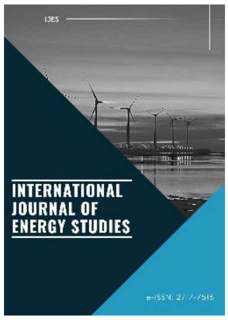

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Hybrid renewable energy systems optimization: A case study of an industrial application using HOMER

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Highlights

- HRES design and optimization for a large-scale factory.
- Optimized system with a COE of 0.0708 $/kWh and a renewable energy ratio of 79.4%.
- A 22% increase in grid electricity prices causes roughly a 7% increase in NPC and COE.
- A 200% increase in RDR leads to a 30% decrease in NPC and a 6% increase in COE.

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ABSTRACT

This study designed four different scenarios for a grid-connected hybrid renewable energy system (HRES) to meet the energy demand of a factory in Balıkesir Organized Industrial Zone. The scenarios, which combine photovoltaic (PV) panels, wind turbines, biogas, and diesel generators, were simulated and optimized using Hybrid Optimization of Multiple Energy Resources (HOMER Pro®) software. The optimization results showed that the most optimal solution is a grid-connected HRES with PV, wind turbines, and a biogas generator, having the lowest net present cost (NPC) of 104 million $ and cost of energy (COE) of 0.0708 $/kWh. This system can supply 79.4% of the factory's electricity demand, which averages 245,560 kWh daily, from renewable sources. The optimal configuration consists of a 4000 kW PV, 6000 kW wind turbine, and 5000 kW biogas generator. Sensitivity analysis revealed that a 22% increase in grid electricity prices results in about a 7% increase in both NPC and COE. Additionally, the effect of changes in the real discount rate (RDR) was analyzed, showing that a 200% increase in RDR leads to a 30% decrease in NPC and a 6% increase in COE.

Keywords: Grid-connected HRES, HRES optimization, sensitivity analysis.

1. INTRODUCTION

Growing global energy demand and climate change concerns have increasingly underscored the importance of renewable energy sources. Conventional fossil fuel based energy generation systems not only lead to the depletion of limited resources but also contribute to global warming through greenhouse gas emissions. Therefore, HRESs have emerged as a significant solution for ensuring energy supply security and sustainability. HRESs integrate multiple renewable energy sources and, if necessary, conventional energy sources to ensure both continuity of energy supply and cost-effectiveness.

While HRES applications are increasing worldwide, significant steps have also been taken in this field in Türkiye. Due to its geopolitical location, Türkiye possesses diverse renewable energy sources, including solar, wind, and biomass. Policies and support mechanisms aimed at increasing renewable energy capacity provide a suitable foundation for the implementation of hybrid energy systems. Various studies have been conducted to ensure the effective utilization of renewable energy resources in Türkiye. In particular, research on the design and optimization of grid-connected and off-grid hybrid energy systems contributes to determining the technical and economic feasibility of such systems.

Accordingly, several studies have been conducted on the design and optimization of grid-connected hybrid energy systems in Türkiye. For instance, Yılmaz et al. [1] modeled different scenarios using the HOMER software to meet the electricity demand of Gökçeada through a system comprising solar panels, wind turbines, and batteries. Their results indicated that wind energy had the lowest cost and that selling excess energy to the grid could be advantageous for Gökçeada. In another study, Mamur et al. [2] conducted a feasibility study on a grid-connected HRES utilizing solar and wind energy to supply electricity to a public building. The analysis, performed using HOMER software, showed that the proposed system could meet the annual energy demand and recover its cost within 7.8 years. In another study using HOMER Pro, Duman and Güler [3] analyzed the economic feasibility of grid-connected rooftop PV systems in Türkiye, concluding that only a southern province was attractive for investment under current conditions. As a result, they suggested developing regional support mechanisms and increasing incentives. Yalılı Kılıç and Adalı [4] designed a grid-connected wind and solar hybrid energy system for a supermarket in the Nilüfer district of Bursa based on its 2020 electricity consumption data using HOMER Pro software. The designed system's unit electricity cost was found to be 0.041 $, with an annual energy saving of 74,254.3 $, leading to an 18-year payback period. In another study, Yalılı Kılıç and Adalı [5] designed a grid-connected PV energy system using HOMER Pro for a building in the Osmangazi district of Bursa. They calculated the NPC value as 49,405.97 TL (5,974.12 $) and the COE value as 0.562 TL/kWh. Another HOMER based study by Yılmaz et al. [6] designed a grid connected HRES to meet the energy demand of an industrial zone in İzmir. The study found that incorporating battery storage reduced the unit electricity cost to 0.073 $ and decreased annual carbon emissions by 82%.

Besides studies using HOMER Pro®, many other HRES optimization studies have also been carried out in Türkiye. One such study by Aktar and Karakılıç [7] optimized a grid connected microgrid that integrates renewable energy sources and energy storage systems to accommodate electric vehicle loads. Their optimization algorithm analyzed four different scenarios, revealing that the economic benefits varied depending on supply-demand balance. Another study by Altın [8] developed a Particle Swarm Optimization (PSO) based tool to overcome HOMER's limitations in processing speed and optimization flexibility. This tool significantly reduced computation time from 936 seconds to 17 seconds, providing a substantial advantage over HOMER while maintaining reliable economic and electrical performance. Additionally, the study introduced the capacity shortage parameter for the first time using metaheuristic algorithms, offering an innovative optimization approach.

In addition to its solar and wind potential, Türkiye has abundant biomass resources, particularly agricultural waste and wood, which are predominantly converted into energy through gasification technology [9, 10]. Studies utilizing this technology are increasing. For instance, Güven and Mete [11] analyzed different scenarios using HOMER software for designing and optimizing a grid-connected HRES in Erdek, Balıkesir, incorporating biogas generators, solar panels, wind turbines, diesel generators, fuel cells, electrolyzers, hydrogen tanks, and batteries. They conducted feasibility studies for three scenarios: diesel and biogas generators, and a hydrogen backup system. The most suitable system was identified as a grid-connected solar/wind/biogas generator/battery system. In another study utilizing biomass gasification technology, Güven and Mengi [9] employed the Atom Search Algorithm to minimize costs while meeting the energy demand of an off-grid HRES powered by wind, solar, and fuel cells.

Globally, numerous studies have explored the potential of biomass gasification technology, especially in remote rural areas. In this context, Murugaperumal and Raj [12] optimized a HRES using solar, wind, and biomass for an off-grid village in India with HOMER software and conducted demand forecasting using artificial neural networks. Another example of biomass-based HRES for off-grid regions was presented by Kumar and Channi [13], who designed a PV/Biomass/Battery system for a rural village in India. They optimized the system using HOMER software and evaluated its optimal configuration using the TOPSIS method, conducting detailed economic and environmental analysis. Araoye et al. [14] examined the techno-economic modeling and optimal sizing of standalone hybrid microgrid systems. Using the Grasshopper Optimization Algorithm (GOA) and HOMER Pro, they conducted a comparative analysis of four different HRES configurations in the Nsukka Community, demonstrating that biogas and PV panels offered the most cost-effective solution. Jasim et al. [15] analyzed the energy management and optimal sizing of a hybrid microgrid system in Basra, Iraq, using real climate and energy demand data. They optimized the system using the Hybrid Grey Wolf and Cuckoo Search Optimization Algorithm, showing that a system comprising solar PV, wind turbines, biogas digesters, batteries, and diesel generators could be designed with the lowest levelized cost of energy (LCOE) (0.1192 $/kWh) and total cost (2.6918 billion $).

Although research on HRESs in Türkiye has been increasing, studies on integrating renewable energy systems into the industrial sector have not yet reached the expected level. In this context, Tabak [16] presented an exemplary study in the literature by focusing on a factory in Konya with an average daily energy demand of 1,000 kWh. The study involved designing a hybrid system comprising PV panels, batteries, and a diesel generator, and HOMER software was employed to evaluate the system's capacity to meet the factory's energy requirements. The system, consisting of 3500 kW of solar panels, a 2400 kW diesel generator, a 55 kWh battery, and a 2885 kW converter, was calculated to have a NPC of 7.81 million USD. The analysis indicated that an annual efficiency loss of 0.81% in the PV panels, a 2% increase in demand, and power outages resulted in energy cost increases of 11.16%, 24.29%, and 2.87%, respectively. In another study, Yalılı Kılıç et al. [17] used the HOMER software to analyze grid-connected and off-grid systems for meeting the energy demand of a textile factory in the Demirtaş Organized Industrial Zone in Bursa, using PV panels.

While these studies demonstrate the feasibility of HRESs in the industrial sector, considering the high energy demand of industrial production, it is clear that existing research needs to be evaluated more comprehensively. The industrial sector holds a significant share in Türkiye's total electricity consumption, accounting for 31.6% according to 2022 data [18]. Furthermore, as of December 2024, it was reported that 57.5% of Türkiye's installed capacity is supplied by renewable energy sources [19]. This high share makes it strategically essential to meet the energy needs of industrial facilities with efficient and sustainable energy sources.

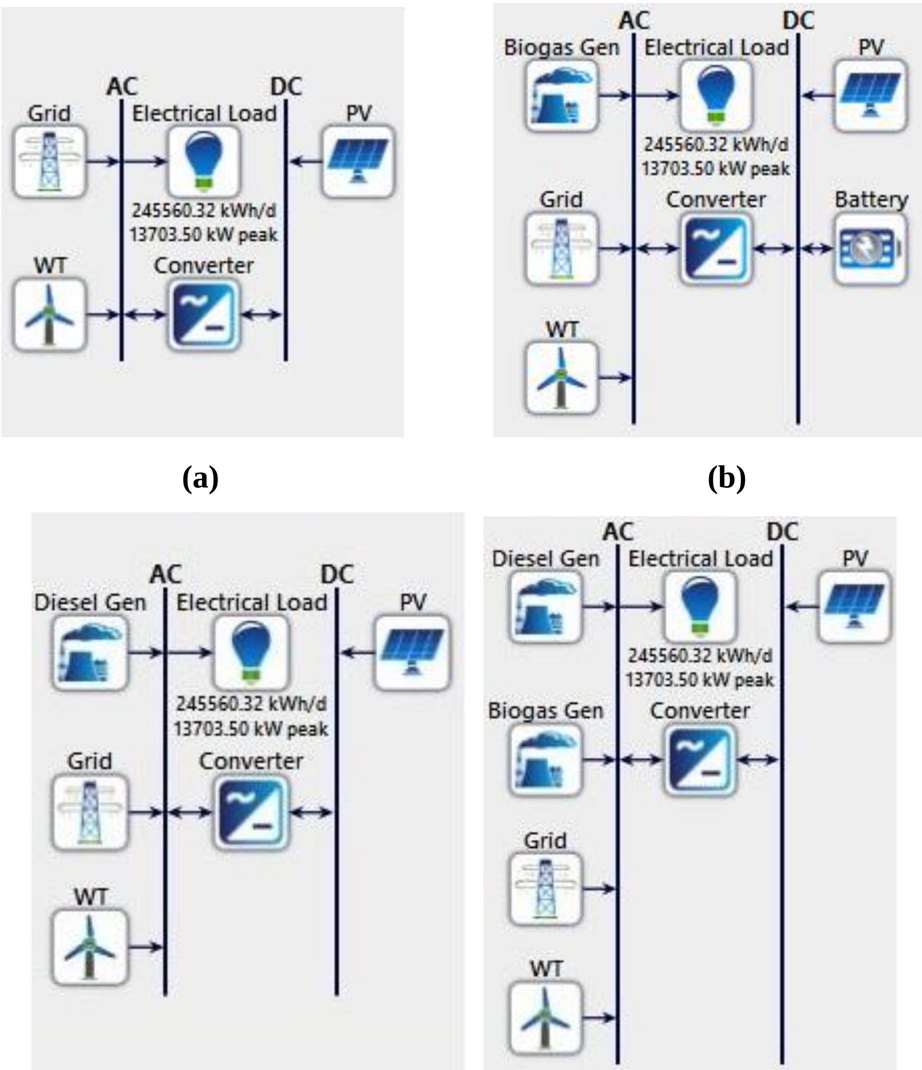
In this context, integrating renewable energy sources into production facilities in Türkiye's organized industrial zones is of critical importance for contributing to the city's economy and reducing its carbon footprint. Balıkesir, one of the cities with a growing industry and increasing energy demand, stands out in Türkiye for its solar and wind energy potential. Additionally, it has significant advantages in renewable energy, with an annual biomass potential of 8,597,445 tons derived solely from animal manure [20]. This study aims to evaluate the existing renewable energy potentials to meet the energy needs of a factory in the Balıkesir Organized Industrial Zone by designing a HRES with four different configurations, thereby highlighting both environmental and economic benefits.

Despite the growth in HRESs research, a gap remains in integrating these systems into industrial sectors in Türkiye, particularly in organized industrial zones. While previous studies have primarily focused on residential or small-scale commercial applications, limited attention has been given to industrial-scale implementations. This study aims to fill that gap by designing and optimizing an HRES for a factory in Balıkesir, using real energy consumption data, with a focus on both environmental and economic impacts. In particular, it presents an alternative HRES solution by evaluating the region's biomass potential and incorporating a biogas generator into the system configuration, which could offer more economical and environmentally advantageous outcomes. Furthermore, sensitivity analyses examine the effects of changes in electricity prices purchased from the grid and fluctuations in the RDR value, which significantly affect costs, on the NPC and COE. As a result, this study provides valuable insights into the integration of HRESs in the industrial sector and introduces a practical model for their implementation.

2. SYSTEM METHODOLOGY

In this study, a grid-connected HRES was designed to meet the energy needs of a factory located in the Organized Industrial Zone of Balıkesir. Simulation and optimization processes were carried out using the HOMER Pro® software. In the designed systems, wind turbines and PV panels were selected as the primary energy sources. The schematic representation of the hybrid system components is presented in Figure 1. To satisfy the factory's energy requirements, four different grid-connected scenarios were developed, with the system components configured as follows:

- Scenario 1 (Figure 1a): Wind turbines, PV panels, and a converter
- Scenario 2 (Figure 1b): Wind turbines, PV panels, a biogas generator, and a converter
- Scenario 3 (Figure 1c): Wind turbines, PV panels, a diesel generator, and a converter
- Scenario 4 (Figure 1d): Wind turbines, PV panels, biogas generator, diesel generator, and a converter



(a) **(b)** **(c)** **(d)**

Figure 1. HRES designed for the factory

(a) Scenario-1 **(b)** Scenario-2 **(c)** Scenario-3 **(d)** Scenario-4

The designed grid-connected HRESs were modeled by considering scheduled maintenance outages and variability in repair times. Accordingly, it was assumed that power outages occur four times per year, each lasting four hours, with a 25% variability in repair durations. Additionally, any potential short-term sudden power outages and voltage fluctuations were not included in the modeling process, as they are compensated for by the existing uninterruptible power supply (UPS) systems.

2.1. System Components

The system components, including PV panels, wind turbines, and biogas generators, have been selected to harness the region's abundant renewable energy potential from solar, wind, and biomass sources (see Sections 2.1.4.1 and 2.2). This selection aims to reduce fossil fuel consumption and provide cost-effective energy solutions, supporting the goal of minimizing environmental impact while meeting the factory's energy needs. The components used in this study were selected from the HOMER Pro® library, and their types, along with technical and economic data, are presented in Table 1.

Table 1. Technical and economic data of the components used in the designed HRES

Component	Type	Capacity	Capital Cost ($)	Replacement Cost ($)	Operation & Maintenance Cost	Lifetime	Ref.
PV	SunPower X21-335	1 MW	600,000	600,000	20,000 $/year	20 years	Commercial*
Wind Turbine	Leitwind 101 2000 kW	2 MW	2,000,000	2,000,000	100,000 $/year	20 years	Commercial*
Biogas Generator	Generic	1 kW	1,000	1,000	0.02 $/kW	20,000 hours	[11]
Diesel Generator	Generic Large	1 kW	500	500	0.03 $/hour	15,000 hours	[21, 22]
Converter	Generic	1 kW	300	300	3 $/year	12 years	[23]

*The technical and economic data for these components were obtained from the respective manufacturers.

2.1.1. PV Panel

In this study, the SunPower X21-335 PV panels available in the HOMER Pro® library were used to simulate the power output derived from solar energy. The power output of a PV panel (P_{PV}) is calculated using Equation (1) [24, 25]:

$$P_{PV} = P_{pv\_rated} \times \frac{R}{R_{stc}} \times (1 + T_{co} \times (T - T_{ref})) \quad (1)$$

Here, P_{pv_rated} represents the nominal power determined under standard test conditions, R represents the incident solar radiation (W/m²), and R_{stc} represents the solar radiation under standard test conditions (1000 W/m²). Additionally, T_{ref} denotes the reference temperature of the cell under standard conditions, T_{co} is the temperature coefficient, and T refers to the cell temperature calculated based on the environmental temperature (T_{ort}) and R. T is calculated using Equation (2) as shown below [24-26]:

$$T = T_{ort} + R \times 0.0256 \quad (2)$$

For the PV system, the maximum power capacity was limited to 4000 kW, considering the maximum sizes that can be installed on the factory's available roof area and land. The PV derating factor is a multiplier applied by HOMER to estimate the output power under actual operating conditions, which is expected to be lower than the nominal power determined under standard test conditions. This factor accounts for temperature, soiling, and other system losses. In this study, the PV derating factor was set at 88%.

2.1.2. Wind Turbine

The hybrid energy system incorporates the Leitwind101 2000 kW wind turbine available in the HOMER Pro® library. To calculate the wind turbine's power output, HOMER first computes the wind speed at the turbine's hub height (V_{hub}) using Equation (3) [24, 25]:

$$V_{hub}(t) = V_{ref}(t) \times \frac{ln(h_{hub}/l_{sr})}{ln(h_{ref}/l_{sr})} \quad (3)$$

In Equation (3), V_{ref} is the reference wind speed at the reference height h_{ref} and h_{hub} is the hub height of the wind turbine. l_{sr} refers to the roughness length, a parameter used to characterize the terrain's surface roughness, which affects wind speed calculations.

After determining the wind speed at the hub height, the power output of the turbine is calculated using the wind turbine power curve under standard temperature and pressure conditions. In this study, the power curve for the wind turbine used in the HRES is shown in Figure 2. To compute the power output under real operating conditions, the power value predicted by the power curve is multiplied by the air density ratio, as expressed in Equation (4):

$$P_g(t) = P_s(t) \times \frac{\rho_g}{\rho_s} \tag{4}$$

In this equation, P_g represents the power generated at the actual air density, P_s is the power calculated at the standard air density, ρ_g denotes the actual air density, and ρ_s refers to the standard air density.

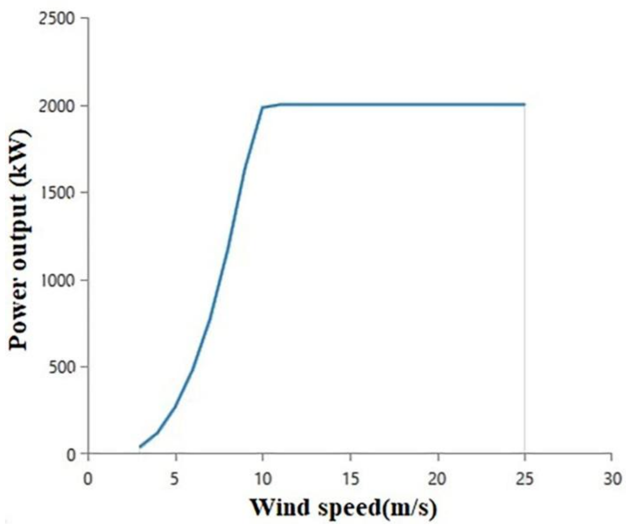


Figure 2. Wind Turbine Power Curve

2.1.3. Diesel Generator

In the hybrid energy system, a diesel generator was selected as one of the units used to meet the load demand and prevent power outages. The generator's minimum load ratio is set at 25%, and it is not operated below this threshold due to inefficiencies. The fuel consumption of the generator (F_{diesel}) is calculated in relation to the instantaneous generator output power (P_{gen}) and the nominal generator power (P_{gen_rated}). The linear model used by the HOMER software is expressed as follows:

$$F_{diesel} = a \times P_{gen} + b \times P_{gen\_rated} \tag{5}$$

In this equation, the coefficients a and b represent the specific fuel consumption parameters of the generator. The diesel fuel price is assumed to be 1 $ per liter. Fuel consumption and operating costs were considered during the system optimization process to determine the optimal generator operating strategy.

2.1.4. Biogas Generator

In this study, a biogas generator that utilizes biomass as fuel was modeled using the biomass module of the HOMER Pro® software. HOMER performs size optimization of the biogas generator by taking into account the available biomass resource.

The specific fuel consumption (SFC), which denotes the amount of biogas required for the biogas generator to produce 1 kW of power, is calculated using Equation (6):

$$SFC = \frac{3.6\ MJ}{\eta \times LHV} \tag{6}$$

Since the LHV is expressed in MJ/kg, a value of 3.6 MJ corresponding to 1 kWh is considered. Here, η represents the electrical efficiency of the generator. The required biomass amount (RBA) is obtained by dividing the specific fuel consumption (SFC) by the biomass gasification rate (O_{bg}):

$$RBA = \frac{SFC}{O_{bg}} \tag{7}$$

The minimum load ratio of the biogas generator was set to at least 30% of its nominal capacity [9]. The biomass gasification rate was assumed to be 75% [9, 27]. The average biomass price was set at 3 $/ton with a carbon content of 5%, and the logistics costs associated with biomass transportation were included in this price. The lower heating value (LHV) of biogas, which represents the amount of energy contained in 1 kg of biogas available for feeding the biogas generator, was taken as 5.50 MJ/kg [28]. Additionally, an intersept coefficient of 0.1 kg/h/kWrated and a slope coefficient of 2.0 kg/h/kWoutput were used for the biogas generator's fuel consumption model.

2.1.4.1. Local Biomass Availability Assessment

To assess the feasibility of biogas generation at the factory scale, it is essential to evaluate the local biomass availability in the region. The factory is located within the Organized Industrial Zone of Balıkesir's Altıeylül district, which has a considerable livestock population and corresponding biomass potential. In this study, an estimation of the biomass potential from cattle in Altıeylül was performed to validate the suitability of the biogas generator integrated into the HRES design.

In line with the system optimization, the maximum capacity selected for the biogas generator is 5000 kW. According to Equation (6), the biomass required to operate a 5000 kW biogas generator is approximately 10,500 kg/h.

In Altıeylül, the number of cattle (N_c) is 74,135. The daily fresh manure amount per cattle (FMA) is approximately 58 kg/day. The usable fraction of this manure, defined as the acquisition rate (AR), is assumed to be 84% [20]. Using these parameters, the total available biomass (TAB) was calculated as 3,611,857 kg/day, which corresponds to 150,495 kg/h, as shown in Equation (8) [20]:

$$TAB = N_c \times AR \times FMA \tag{8}$$

Considering the optimized maximum biogas generator capacity of 5000 kW and the corresponding biomass consumption of approximately 10,500 kg/h, it is evident that the available biomass potential from cattle alone in Altıeylül is nearly 15 times greater than the required amount. This indicates that the local biomass potential is more than sufficient to support the biogas generator's fuel requirements.

2.2. Location Data and Load Profile

In this study, the location considered is a factory in the Organized Industrial Zone of Balıkesir, a province in western Türkiye. Balıkesir, which spans the Marmara and Aegean regions, is strategically positioned and exhibits high potential for renewable energy resources. With geographical coordinates of 39°35'3" N and 27°50'15" E, Balıkesir records an average annual solar irradiation of 1422 kWh/m², an average daily radiation of 4.19 kWh/m²/day, and an average annual wind speed of 5.43 m/s [29, 30]. Hourly meteorological data including wind speed, solar radiation, and temperature were evaluated in the simulations using the "NASA Surface Meteorology and Solar Energy" database available in HOMERPro™. Graphs of these data are presented in Figures 3, 4, and 5, respectively.

Figure 3. Average wind speed values for Balıkesir province

Figure 4. Radiation and clearness index values for Balıkesir province

Figure 5. Average temperature values for Balıkesir province

In this study, actual electricity consumption data from the factory for the year 2024 was used to perform an hourly energy flow simulation. Figure 6 presents the factory's monthly load profiles. The factory's average daily electricity consumption throughout the year was determined to be 245,560.32 kWh. The highest daily load was observed in August, reaching 13,703.5 kW, while the highest monthly average consumption was also recorded in August at 11,138.53 kW, and the lowest in December at 8,819.47 kW.

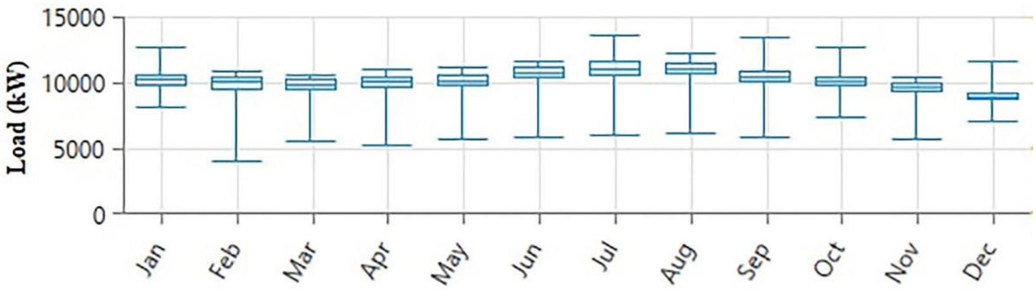


Figure 6. Monthly Average Load Profile

3. SYSTEM COST AND PERFORMANCE PARAMETERS

3.1. System Cost

The HOMER software evaluates the cost analysis of energy systems based on NPC and COE calculations. These calculations are crucial for the economic assessment and comparison of an energy system.

NPC is defined as the difference between the present value of all capital, replacement, operation, and maintenance costs incurred over the lifetime of an energy system and the present value of all revenues generated during the same period [31, 32]. HOMER calculates this cost using Equation (9):

$$NPC = \frac{C_{ann}}{CRF(ir,R)} \tag{9}$$

where C_{ann} represents the total annualized cost ($/year). The annual cost formula used in HOMER converts capital and other lifetime costs into equal annual payments. The Capital Recovery Factor (CRF), which discounts future costs to present value, is calculated using Equation (10) [33]:

$$CRF\,[ir, R] = \frac{ir\,[1+ir]^R}{[1+ir]^R - 1} \tag{10}$$

where R represents the system lifetime (years), and dr_{real} denotes the RDR, which is determined by Equation (11) [33], based on the nominal discount rate ($dr_{nominal}$) and the annual inflation rate (fr):

$$dr_{real} = \frac{dr_{nominal} - fr}{1 + fr} \tag{11}$$

COE represents the total cost per unit of generated energy. In HOMER, this cost is calculated using Equation (12):

$$COE = \frac{C_{ann}}{E_{tot} + E_{şs}} \tag{12}$$

In Equation (12), E_{tot} (kWh/year) represents the total annual energy production, while $E_{şs}$ (kWh/year) denotes the total amount of energy sold to the grid annually.

In HOMER software, the operating cost is calculated as the annualized value of all costs and revenues, excluding initial investment costs. The operating cost (C_o) is determined by the difference between the total annualized cost (C_{tann}) and the total annualized capital cost (C_{tac}). In HOMER, C_o is expressed by Equation (13):

$$C_o = C_{tann} - C_{tac} \tag{13}$$

The total annualized capital cost (C_{tac}) is calculated using the system's total initial investment cost (C_{inv}) and the CRF, as given in Equation (14):

$$C_{tac} = C_{inv} \times CRF(ir, R) \tag{14}$$

3.1.1. Financial Assumptions used in Cost Calculations

In this study, a nominal interest rate of 6% and an annual inflation rate of 2% were assumed, resulting in an RDR of 3.92% as computed via Equation (11). These values were used consistently in all NPC and COE calculations. The project lifetime was set to 25 years for all designed HRESs.

When the electricity generated by the HRES is insufficient to meet the load demand, the deficit is supplied by purchasing electricity from the grid at a price of 0.12 $/kWh. Conversely, when the electricity generated by the HRES exceeds the load demand, the surplus electricity is sold to the grid at a price of 0.06 $/kWh. Table 2 summarizes the key financial parameters.

Table 2. Key financial parameters

Parameter	Value	Unit
Nominal discount rate	6	%
Annual inflation rate	2	%
RDR	3.92	%
Project (system) lifetime	25	years
Grid electricity purchasing price	0.12	$/kWh
Grid electricity sellback price	0.06	$/kWh

3.2. Renewable Energy Ratio

In this study, the renewable energy ratio (RER) is considered a key criterion for evaluating the performance of the designed HRESs. This ratio is an important indicator for assessing the system's environmental sustainability and analyzing the level of renewable resource utilization.

RER is defined as the ratio of annual electricity generation from renewable energy sources, such as solar, wind, hydro, and biomass, to the total electricity generation. It serves as a crucial parameter for evaluating the environmental sustainability of the system and is calculated using the following Equation (15):

$$RER\ (\%) = \frac{E_{RE}}{E_T} \times 100 \tag{15}$$

Here, E_{RE} represents the total energy (kWh) generated from renewable energy sources, while E_T denotes the total electricity generation (kWh) within the system. The total energy generated from renewable sources includes electricity production from PV panels, wind turbines, hydroelectric systems, and biomass generators, whereas the total system electricity generation accounts for energy produced from both renewable and non-renewable sources.

In HOMER software, this ratio is used to measure the contribution of renewable energy sources to system performance. A high RER indicates the effectiveness of renewable resources in the system and their environmental benefits.

Based on the simulation results provided by HOMER, the RER values have been separately calculated and evaluated for four different scenarios. Scenarios with higher RER values offer more sustainable solutions both economically and environmentally.

4. OPTIMUM SYSTEM RESEARCH

In this study, the performance of four different HRES designs, intended to meet the energy demands of a factory in the Balıkesir Organized Industrial Zone, was analyzed using HOMER Pro® software over a 25-year lifespan, considering economic, environmental, and technical criteria. To determine the optimal component configuration, different capacity options were assessed, and Table 3 presents the size options of the system components analyzed.

Table 3. System components' size optimization options

Component	Size Options
PV	2000 kW, 4000 kW
Wind Turbine (2000 kW)	2 units, 3 units
Biogas Generator	3000 kW, 4000 kW, 5000 kW
Diesel Generator	3000 kW, 4000 kW, 5000 kW
Battery	HOMER Optimizer
Converter	HOMER Optimizer

Based on the analyses, the optimal values for various criteria such as NPC, COE, operational costs, initial investment costs, RER, and fuel consumption for four different scenarios are summarized in Table 4.

Table 4. Optimization results of the designed HRES

Scenario No	PV (kW)	Wind Turbine (Units)	Biogas Generator (kW)	Diesel Generator (kW)	Converter (kW)	NPC ($)	COE ($/kWh)	Opera-tional Cost ($)	Initial Investment Cost($)	RER (%)	Total Fuel (ton/year)
1	4000	3	-	-	3105	126 M	0.0895	7.42 M	9.33 M	35.2	-
2	4000	3	5000 (Bio gen)	-	2998	104 M	0.0708	5.72 M	14.3 M	79.4	119738
3	4000	3	-	5000	3105	128 M	0.0909	7.39 M	11.8 M	35.2	23598
4	4000	3	5000	3000	2998	106 M	0.0716	5.7 M	15.8 M	79.4	119763 (biomass) +11389 (diesel)

When Table 4 is examined, the most advantageous scenario in terms of NPC and COE is Scenario-2, with NPC of 104 M$ and COE of 0.0708 $/kWh. The primary reason for this is the low capital and operating costs, as well as the long lifespan of the biogas generator. Scenario-4, while having slightly higher cost values compared to Scenario-2 due to the inclusion of both biogas and diesel generators, offers a competitive option, particularly in the case of power outages, thanks to the presence of the diesel generator. The highest NPC value of 128 M$ and the highest COE value of 0.0909 $/kWh are observed in Scenario-3. In Scenario-1 and Scenario-3, only wind turbines and PV panels are used instead of the biogas generator. However, in these systems, the RER is 35.2%, and the total energy cost increases due to high grid dependency. The differences in NPC and COE values between Scenario-3 and Scenario-1 arise from the use of diesel generators. In conclusion, it is evident that the use of the biogas generator provides a cost advantage and significantly reduces the system's dependency on the grid.

In addition to economic and technical indicators, the environmental impact of each scenario was also assessed in terms of carbon dioxide emissions. Table 5 presents the annual carbon dioxide emissions and the corresponding reduction percentages, compared to the existing system, for the optimum HRES configurations in each scenario.

Table 5. Yearly emission values of optimum HRES of each scenario

Scenarios	Carbon Dioxide Values (ton/yr)	Reduction (%)
Scenario-1	36,645.286	35%
Scenario-2	12,227.195	78%
Scenario-3	36,707.165	35%
Scenario-4	12,247.549	78%
Baseline (Existing system)	56,676.095	-

As shown in Table 5, Scenario-2 and Scenario-4 resulted in the highest carbon dioxide emission reductions of 78%, thanks to the integration of the biogas generator. In contrast, Scenario-1 and Scenario-3 achieved only a 35% reduction due to their higher dependency on grid electricity. The baseline case, representing the existing system, recorded the highest annual carbon dioxide emissions of 56,676.1 tons per year, as it relies solely on grid electricity and uses a diesel generator during power outages.

Following the environmental evaluation, Figure 7 shows the distribution of cost types for the four different scenarios. According to the cost analysis results, Scenario-2 stands out as the most economically advantageous configuration with the lowest NPC value of 104.44 M$. In this scenario, 13.7% of the total cost is the initial investment cost, 33.1% is replacement cost, 50.0% is operating and maintenance costs, and 5.4% is fuel costs.

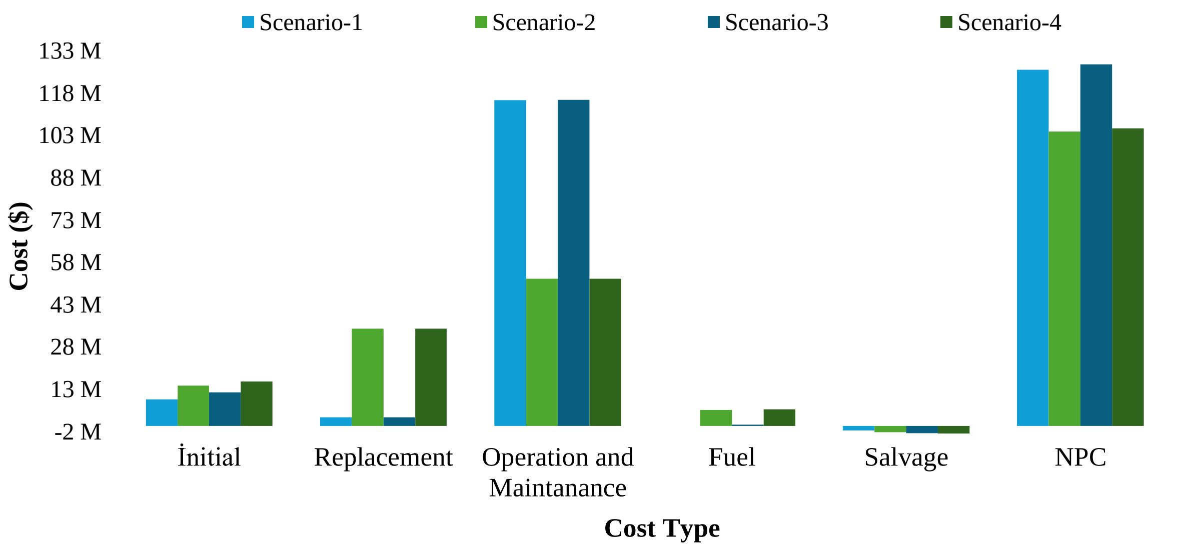


Figure 7. Comparison of cost types for four different scenarios

Table 6 presents the amount of electricity produced by system components in each scenario and their respective shares in total production. While the annual total electricity production from PV panels and wind turbines remains the same across all scenarios, the inclusion of generators has caused changes in the amount of electricity that needs to be purchased from the grid. In Scenario-2 and Scenario-4, the use of the biogas generator allows for a RER of 79.4%. The biogas generator significantly increases the renewable energy contribution with a 45.5% share of production, reducing the system's grid dependency to approximately 21%.

On the other hand, in Scenario-1 and Scenario-3, where only wind turbines and PV panels are the main production sources and the biogas generator is not used, RER remains at 35.2%, and the system's grid dependency rises to 64.5%. Additionally, in Scenario-3, the use of the diesel generator, with its high operating and maintenance costs alongside fuel costs, was only used during power outages, occurring four times a year. In Scenario-3, as in Scenario-1, the remaining electricity demand not met by PV and wind turbines was purchased from the grid. This situation results in high NPC and COE values in Scenario-3, similar to Scenario-1, due to the system's high grid dependency.

Table 6. Annual electricity production and contribution of system components in each scenario

Produced Electricity	Scenario-1		Scenario -2		Scenario-3		Scenario-4	
	kWh/year	**%**	**kWh/year**	**%**	**kWh/year**	**%**	**kWh/year**	**%**
PV	5,835,463	6.49	5,835,463	6.21	5,835,463	6.49	5,835,463	6.21
Biogas Generator	-	-	42,762,819	45.50	-	-	42,772,118	45.50
Diesel Generator	-	-	-	-	70,243	0.08	30,889	0.03
Wind Turbine	26,051,727	29.00	26,051,727	27.70	26,051,727	29.00	26,051,727	27.70
Grid	57,983,047	64.5	19,312,689	20.60	57,983,047	64.50	19,297,634	20.50
Total	89,870,236	100	93,962,698	100	89,940,479	100	93,987,831	100
Excess Electricity	57,847	0.064	85,333	0.091	57,847	0.064	85,333	0.091
Unmet Electricity Load	113,053	0.126	27,863	0.031	42,811	0.048	15,153	0.0169

4.1. Simulation Results for the Optimal Solution

The most suitable system configuration determined during the optimization process was obtained by considering technical and economic performance criteria. In this context, the technical and economic parameters, including power capacity, production performance, and cost values for the system components under Scenario 2, which was identified as the optimal solution, are presented in Table 7.

Table 7. Technical and economic data of the system for the optimal solution (scenario 2)

System Components	Rated Power (kW)	Minimum Output Power (kW)	Maximum Output Power (kW)	Average Output Power (kW)	Capacity Factor (%)	Operating Hours (hours/ year)	Levelized Cost ($/kWh)	Marginal Production Cost ($/kWh)
PV	4000	0	4335	666	16.7	4389	0.0398	-
Wind Turbine	6000 (2000kW*3units)	0	6000	2974	49.6	7747	0.0285	-
Biogas Generator	5000	2.389	5000	4998	97.6	8556	-	0.008

Figure 8 presents the annual power flow profile for the optimal solution corresponding to Scenario 2. In Figure 8(a), the annual power outputs of the PV panels (orange lines), wind turbines (purple lines), and biogas generator (brown lines) are shown, along with the electricity purchased from the grid (light blue lines) and the overall electrical load served (dark blue lines). It is observed that the production of the PV systems increases during the summer months due to longer sunshine durations, whereas the contribution of the wind turbines remains relatively constant throughout the year. Importantly, Figure 8(a) highlights the critical role of the biogas generator, which continuously compensates for the seasonal fluctuations of PV and wind power by providing a steady maximum output of 5000 kW. This feature ensures a stable and reliable electricity supply, especially during periods of low renewable generation.

In Figure 8(b), the periods during which excess electricity is sold to the grid when the system's power generation exceeds the load demand are indicated by green lines. The occurrence of unmet electricity load (red lines) is limited to a few instances, which mainly correspond to grid outage periods when the combined power output of the PV panels and wind turbines is insufficient to meet the demand. The deficiency in the combined power production of the PV panels and wind turbines is effectively compensated by the biogas generator, which consistently provides a maximum power output of 5000 kW throughout the year, thereby playing a crucial role in fulfilling the electricity demand.

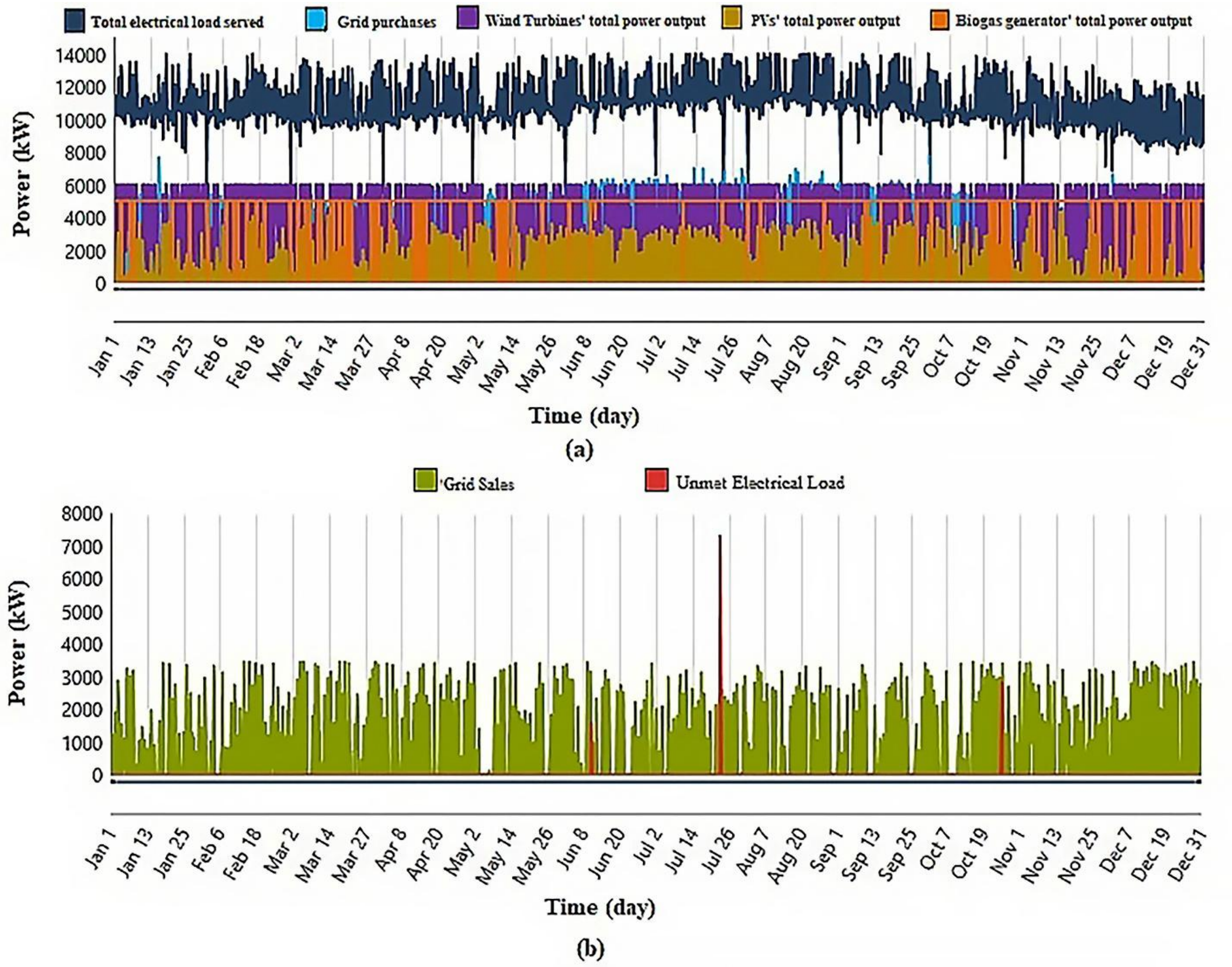
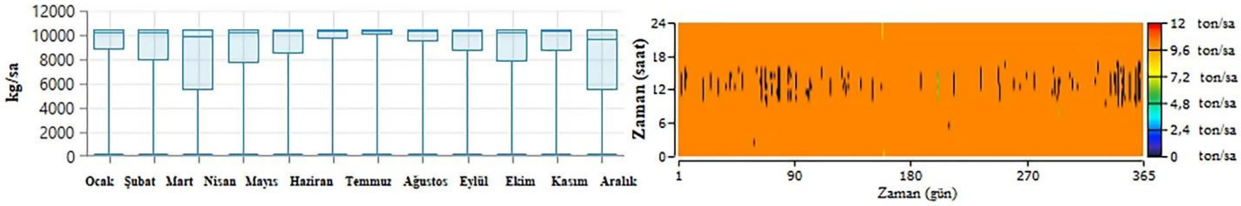


Figure 8. Power Flow of System Components for the Optimal Solution in Scenario 2

Figure 9 presents the fuel consumption values for the optimal solution obtained for Scenario 2. Accordingly, the total fuel consumption was calculated to be 119,738 tons, with an average daily consumption of 328 tons/day and an average hourly consumption of 13.7 tons/hour. The biogas generator exhibited a specific fuel consumption of 2.10 kg/kWh, a fuel energy input of 137,200,004 kWh/year, electricity production of 42,762,819 kWh/year, and an average electrical efficiency of 31.2%.



(a) **(b)**

Figure 9. Annual Biomass Fuel Consumption for Scenario 2

(a) Monthly Average Hourly Fuel Consumption **(b)** Hourly Fuel Consumption

4.2. Sensitivity Analysis

When analyzing the optimal results across all four scenarios, it is evident that the electricity purchased from the grid constitutes a significant portion of the overall system cost. To better understand this impact, a sensitivity analysis was performed to examine the changes in NPC and COE values when the grid electricity purchase price is decreased or increased by 5% and 10%. In addition, the effect of the RDR value on both COE and NPC was analyzed concurrently. Figure 10 presents the sensitivity analysis results, illustrating how variations in the grid electricity purchase price and the RDR value influence the NPC and COE values of the optimum solution corresponding to Scenario 2.

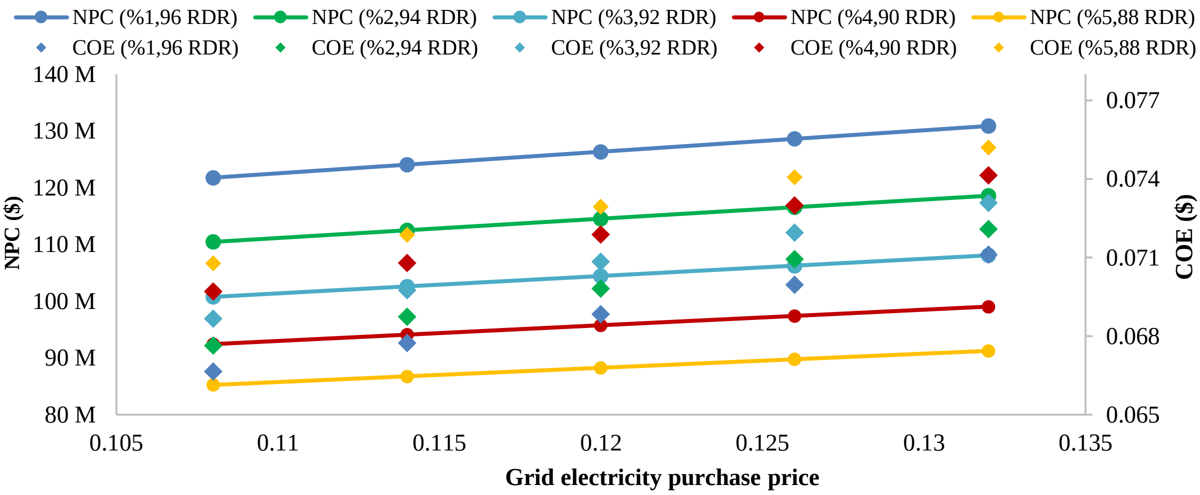


Figure 10. The Effect of Grid Electricity Purchase Price and RDR on NPC and COE

The RDR is the discount rate with the effect of inflation removed, reflecting the actual purchasing power. In finance and economics, it is used to calculate the present value of future cash flows. In energy projects, discounting future revenues or savings to their present value while accounting for inflation allows for a more realistic assessment. The use of RDR instead of nominal discount rate helps eliminate misleading effects caused by inflation in investment decisions [34, 35, 36]. Given that the RDR can vary based on inflation, interest rates, and economic fluctuations, it is a critical parameter to consider in sensitivity analyses [37].

When examining Figure 10, it is evident that an increase in the grid electricity purchase price leads to a linear rise in both NPC and COE. Specifically, raising the grid electricity purchase price from 0.108 $/kWh to 0.132 $/kWh (a 22% increase) results in approximately a 7% increase in both NPC and COE.

Furthermore, when the grid electricity purchase price is held constant, a 200% increase in the RDR (from 1.96% to 5.88%) results in a 30% decrease in NPC and a 6% increase in COE. These results indicate that while an increase in RDR reduces NPC, it simultaneously raises COE. This is because as RDR increases, future costs are discounted more heavily, leading to a lower NPC. However, since the present value of capital costs rises, COE increases.

5. CONCLUSION AND EVALUATION

In this study, a large-scale factory in Balıkesir was selected to demonstrate the economic and technical feasibility, as well as the sustainability, of grid-connected HRESs in Türkiye’s organized industrial zones. To utilize the region’s high wind, solar, and biomass energy potential, four different scenarios were developed, and an optimization study was conducted using HOMER Pro® software. The optimal solutions for each scenario were analyzed, and the scenario with the lowest NPC and COE values was selected for detailed simulation and sensitivity analysis. Accordingly, the key findings of the study can be summarized as follows:

- The lowest NPC and COE were achieved in Scenario 2, which incorporated a biogas generator.
- The highest RER of 79.4% was obtained in both Scenario 2 and Scenario 4, where a biogas generator was utilized.
- The biogas generator, contributing 45.5% of total production, significantly reduced the system’s grid dependency and provided an economic advantage.
- Scenario-2 and Scenario-4, which incorporated the biogas generator, resulted in the highest carbon dioxide emission reductions of 78%.

- Systems consisting solely of wind turbines and PV panels (Scenarios 1 and 3) were found to be economically disadvantageous due to their high grid dependency.
- A 22% increase in the grid electricity purchase price resulted in approximately a 7% rise in NPC and COE, highlighting the strong influence of electricity purchase costs on overall expenses.
- A 200% increase in the RDR led to a 30% reduction in NPC and a 6% increase in COE.

In conclusion, these findings offer significant practical implications for the industrial sector: the integration of HRES—especially through the incorporation of biogas generators—presents a scalable, cost-effective, and environmentally friendly strategy that can be directly applied to similar industrial settings. Furthermore, this study is expected to encourage and guide future research, particularly those conducting more detailed analyses across different OSBs in Türkiye and exploring alternative solutions, such as hydrogen storage.

DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Tuba Tezer: Conceptualization, methodology, investigation, modeling, visualization, data analysis, resources, manuscript writing, and editing.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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