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ENERGY & FUELS

112/182

JCR YEAR	JIF RANK	QUARTILE	JIF PERCENTILE
2024	112/182	Q3	38.7
2023	108/171	Q3	37.1

Rank by JIF before 2023 for ENERGY & FUELS

EDITION

Science Citation Index Expanded (SCIE)

JCR YEAR	JIF RANK	QUARTILE	JIF PERCENTILE
2022	80/119	Q3	33.2
2021	80/119	Q3	33.19
2020	70/114	Q3	39.04
2019	63/112	Q3	44.20
2018	56/103	Q3	46.12
2017	48/97	Q2	51.03
2016	45/92	Q2	51.63
2015	43/88	Q2	51.70
2014	43/89	Q2	52.25
2013	43/83	Q3	48.80
2012	38/81	Q2	53.70
2011	35/81	Q2	57.41
2010	42/79	Q3	47.47

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CATEGORY

ENERGY & FUELS

123/182

JCR YEAR	JCI RANK	QUARTILE	JCI PERCENTILE
2024	123/182	Q3	32.69
2023	116/174	Q3	33.62
2022	99/155	Q3	36.45
2021	93/145	Q3	36.21
2020	81/133	Q3	39.47
2019	73/132	Q3	45.08
2018	70/131	Q3	46.95
2017	68/126	Q3	46.43

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Article

Optimization of Grid-Connected and Off-Grid Hybrid Energy Systems for a Greenhouse Facility

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Abstract

This study evaluates the technical, economic, and environmental feasibility of grid-connected and off-grid hybrid energy systems designed to meet the energy demands of a greenhouse facility. Various system configurations were developed based on combinations of solar, wind, diesel, and battery storage technologies. The analysis considers a daily electricity consumption of 369.52 kWh and a peak load of 52.59 kW for the greenhouse complex. Among the grid-connected systems, the grid/PV configuration was identified as the most optimal, offering the lowest Net Present Cost (NPC) of USD 282,492, the lowest Levelized Cost of Energy (LCOE) at USD 0.0401/kWh, and a reasonable emissions reduction of 54.94%. For off-grid scenarios, the generator/PV/battery configuration was the most cost-effective option, with a total cost of USD 1.19 million and an LCOE of USD 0.342/kWh. Environmentally, this system showed a strong performance, achieving a 64.58% reduction in CO_2 emissions; in contrast, fully renewable systems such as PV/wind/battery and wind/battery configurations succeeded in reaching zero-emission targets but were economically unfeasible due to their very high investment costs and limited practical applicability. Sensitivity analyses revealed that economic factors such as inflation and energy prices have a critical effect on the payback time and the Internal Rate of Return (IRR).

Keywords: hybrid energy systems; renewable energy; greenhouse energy management; LCOE; environmental sustainability; economic feasibility

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1. Introduction

The depletion of fossil fuel reserves, along with environmental concerns such as climate change and the increase in global energy demand, has necessitated a shift toward renewable energy sources. Global electricity generation reached 29.5 TWh in 2023 (Figure 1), and approximately 30.3% of this came from REN sources [1]. This share is projected to exceed 45% by 2030 [2]. In particular, solar and wind energy systems have been increasingly adopted in energy generation due to declining costs and ongoing technological advancements.

In Türkiye, total electricity generation reached 349 TWh in 2024. Of this, 42% (137.2 TWh) came from REN sources and 44% from fossil fuels [3]. Meanwhile, electricity consumption in 2024 increased by 3.8% compared with the previous year, reaching 347.9 TWh. Projections indicate that electricity consumption will grow at an average annual rate of 4.8%, reaching approximately 450 TWh by 2030.

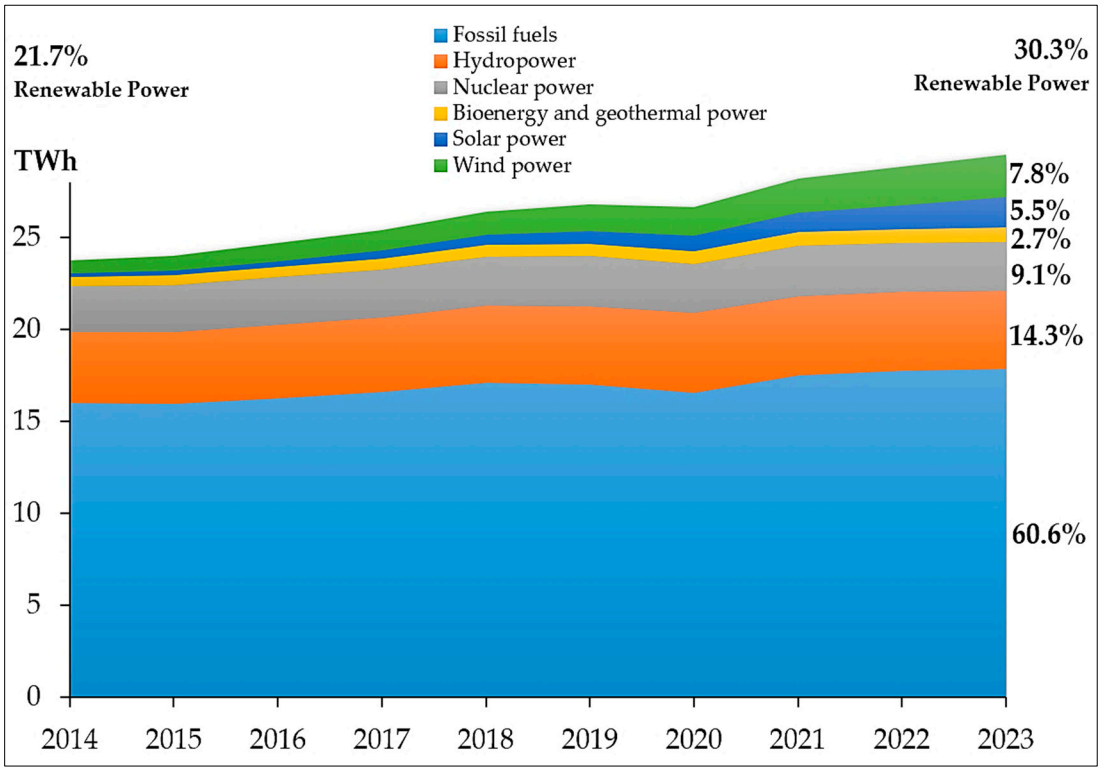


Figure 1. Electricity generation by energy source, 2014–2023 (data source: EMBER, modified by author) [1].

Türkiye has a high potential for renewable energy sources such as solar and wind energy. Türkiye has an average annual solar radiation of 1527.46 kWh/m^2 per year (or 4.18 kWh/m^2 per day), and a total annual sunshine duration of 2741 h (7.5 h per day) [4]. Moreover, Türkiye's wind energy potential is estimated to be 47,850 MW, with particularly high potential in the western and southwestern regions, where average wind speeds exceed 7.5 m/s annually [5].

Despite its strong REN potential, Türkiye's energy sector remains largely dependent on fossil fuels. Therefore, the Ministry of Energy and Natural Resources introduced a revised Renewable Energy Support Mechanism (YEKDEM) in 2021 to promote the use of REN and reduce fossil fuel consumption in electricity production [6]. This mechanism was revised again in May 2023 to better align with evolving needs [7]. Along with ongoing reforms in the electricity sector, improvements in REN technologies, falling costs, and government-backed financial incentives have increased interest in REN investments [8]. By the end of 2023, renewable sources accounted for 55% of Türkiye's total installed capacity, which reached 106.7 GW [9]. Of the 2873 MW of new installed capacity added in 2023, 1890 MW (65.8%) came from solar energy, 414 MW (14.4%) from wind, and 393 MW (13.7%) from hydropower plants (Figure 2) [9,10]. As of March 2025, Türkiye's installed power capacity had risen to 118.2 GW, with approximately 70 GW derived from renewable sources, raising the renewable share of electricity production capacity to 60% [11,12].

According to the National Energy Plan (UEP) [13,14], Türkiye's total installed capacity is expected to reach 189.7 GW by 2035. The share of renewables is projected to increase to approximately 65% of total capacity and approximately 55% of electricity generation. By 2035, wind and solar energy are expected to account for 43.5% of the installed capacity and 34.2% of total electricity generation.

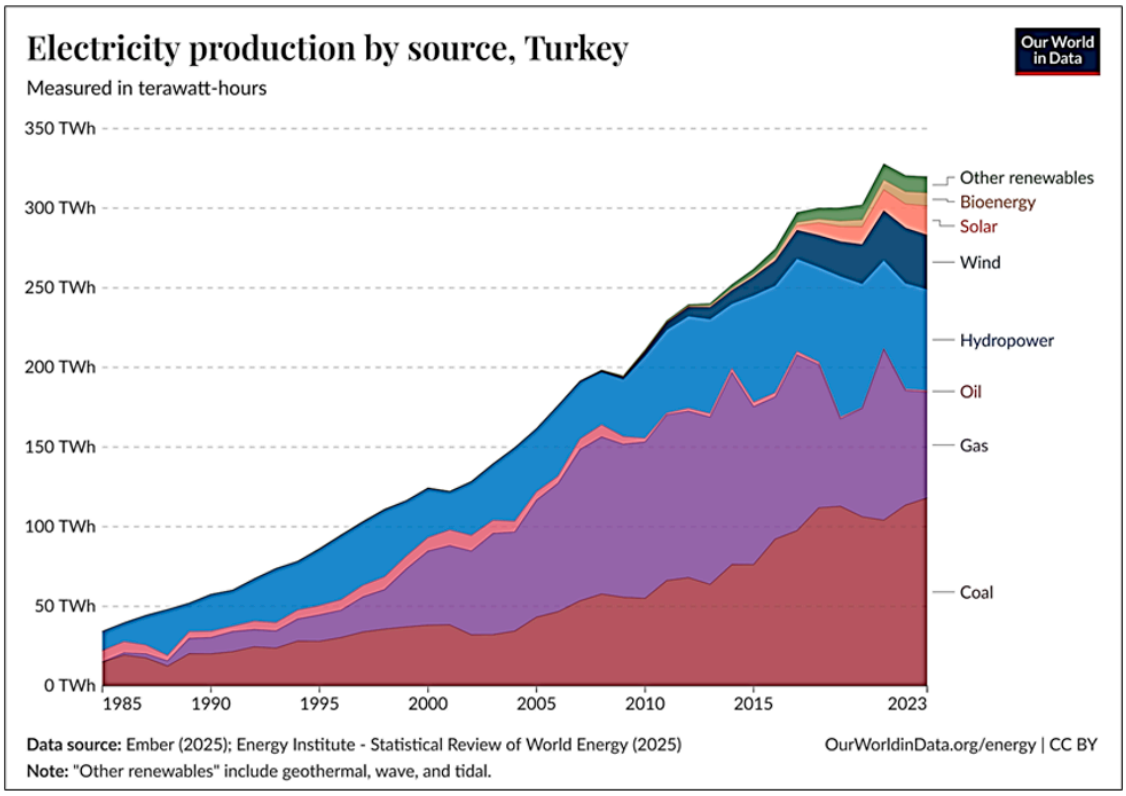


Figure 2. Electricity production by source, Türkiye (data source: Ember (2025) Energy Institute—Statistical Review of World Energy (2025)—with major processing by Our World in Data) [10].

1.1. Renewables in Agriculture

In 2021, the share of REN in total final energy consumption was highest in the industrial sector, at 16.8%, while the agricultural sector accounted for 15.4%. These discrepancies stem not only from the structural characteristics of each sector but also from the lack of comprehensive and integrative policies aimed at increasing the share of renewables [15,16].

Moreover, policies related to energy use in agriculture often lack consistency, resulting in inconsistencies. For example, tax incentives provided for diesel fuel in agriculture have caused farmers to hesitate in making investments in REN technologies [17,18]. In this context, more decisive action is needed to increase the level of electrification across sectors and to facilitate the transition to REN.

Among the key benefits for farmers adopting REN and energy efficiency practices are improved access to energy and a higher level of reliability, reduced fuel costs, decreased food loss, and enhanced mechanization. Additional advantages include extended production seasons, access to new markets, and positive environmental and health-related impacts [19,20]. Farmers using REN-powered cooling technologies reported income increases of up to 40%. As of the end of 2023, four countries and the European Union had established REN targets specifically for the agricultural sector. For instance, as of 2022, of the total 1165 MW of off-grid solar-powered irrigation systems installed globally, 1083 MW were installed in India. India also announced its intention to replace diesel fuel use in agriculture with REN by 2030. South Korea, on the other hand, has set a target of reaching 10 GW of agrivoltaic system capacity by 2030 [21]. The European Union, through its Common Agricultural Policy (CAP) for 2023–2027, aims to reach 1.5 GW of REN capacity in agriculture by 2027. This policy supports investments in REN, including biogas production on farms, with plans to establish 1556 MW of new REN capacity [22]. CAP supports the participation of approximately 180,000 farms in REN initiatives and promotes

energy efficiency and precision agriculture for improved resource management [22]. The European Commission also published an energy transition strategy for the EU's fisheries and aquaculture sectors [23].

Recently, agrivoltaic applications, which allow for the simultaneous production of crops and energy while enabling more efficient use of agricultural land, have gained prominence. Germany, France, and Japan are leading countries in agrivoltaic practices, with others following suit through pilot projects [24]. Notable examples include the 7 MW Grosolar agrivoltaic facility in Maharashtra and the 3 MW Solar-Agri electricity model in Gujarat, both in India [25]. Studies in Portugal demonstrated that agrivoltaic systems are more efficient than either standalone agriculture or solar energy production. The electricity generated serves both for self-consumption and grid sales, creating a diversified income stream [26]. As of 2024, the USA installed 73 MW of agrivoltaic capacity on cultivated farmland and over 5 GW on grazing lands [27]. In 2023, Türkiye launched its first agrivoltaic project with a capacity of 122 kW [28].

Solar-powered mini-grid projects are improving energy access for agricultural operations such as water pumping for irrigation, food drying, milling, and cold storage [29]. Given that most rural agricultural energy demand occurs during daylight hours, installing mini-grids near farmland offers a practical solution to meet this demand [30]. In Nigeria, ongoing projects enable farmers to carry out production-related activities using electric vehicles and have provided power for rice and grain mills as well as cold storage facilities used in fish processing [31]. In Uganda, a 600 kW battery-supported hybrid solar mini-grid established on the Lolwe Islands replaced fossil fuel usage in applications such as ice production and fish drying [32].

1.2. Studies Focusing on Renewable Energy Optimization Strategies

The use of REN sources in rural areas is very important for sustainable development. Households in remote or isolated regions [33], along with agricultural businesses and industrial complexes, can obtain electricity from commercial microgrids [34]. Advanced modeling and simulation tools are employed in the planning and feasibility evaluation of such systems. HOMER Pro (Hybrid Optimization Model for Electric Renewables) is a powerful tool used to optimize microgrid architecture and ensure maximum operational efficiency [35]. In HOMER Pro, various combinations of components, including photovoltaic (PV) panels, wind turbines, battery storage, and fuel cells, can be efficiently optimized for both grid-connected and standalone systems [36]. Models developed using the HOMER Pro software can determine the most cost-effective energy system for a given geographical area. Optimal configurations can be derived using both optimization and sensitivity analyses.

In applications focusing on the optimization of grid-connected large-scale wind and PV systems [37–39], researchers found that wind energy systems may be more cost-effective than photovoltaic systems [40]. Some studies concluded that solar–diesel hybrid power systems are more sustainable for rural areas [41]. However, when generators are used instead of grid connections in hybrid systems combining wind and solar energy, the initial investment cost increases by 4–5 times, and the payback period extends by 5–8 times [42]. In a study conducted in southern Ghana, the technical and economic feasibility of a hybrid system incorporating solar, wind, and diesel generators was assessed [43–45], and optimal configurations were identified based on LCOE and NPC. These findings enabled policymakers and stakeholders in Ghana to shape strategic energy goals. Another study conducted in rural Malaysia revealed that standalone wind–solar hybrid systems were more stable and economical than single-source systems [46–49]. These results support the thought that independent hybrid REN systems are among the most reliable options for ensuring a continuous power supply in rural areas at lower LCOE values [50,51]. Despite the

growing body of literature, most existing studies investigate only one or two configurations in isolation and therefore lack a systematic comparison of multiple hybrid architectures under consistent technical and economic assumptions.

Environmental impact assessment is another important aspect of hybrid energy systems. In optimization efforts, one of the goals, besides minimizing LCOE, is to reduce emissions of gases such as CO_2, SO_2, and NO_x [52–54]. For example, the optimization of a hybrid energy system supported by batteries, featuring a combination of PV, wind turbines, and a diesel generator, demonstrated a significant reduction in carbon emissions. Specifically, the system achieved an approximate 62% decrease in emissions compared with a fossil fuel-only system while maintaining a low LCOE [55,56].

The main objectives of integrating various REN sources into Hybrid Renewable Energy Systems (HRESs), including PV/hydro/diesel, PV/diesel/wind, PV/hydro/wind, or PV/hydrogen/fuel cell/wind combinations, are to improve the efficiency, reliability, and availability of electricity generation in both rural and urban settings [57–66]. It is also recommended that standalone hybrid systems be paired with battery storage systems to improve reliability and performance [67]. Integrating solar and wind energy with battery or grid electricity can yield a more cost-effective HRES capable of delivering reliable power 24/7. Lithium batteries are particularly well-suited for energy storage in standalone hybrid systems [68–76]. Some studies have shown that adding a battery bank to PV–wind hybrid systems can reduce grid dependency from 45% to 24%, while increasing the energy supply reliability from 65% to 76% [77]. Design optimization of these hybrid systems to reduce energy production costs is a rapidly evolving research area. Addressing challenges associated with battery use, particularly those affecting cost, is an integral part of this research. One such issue is the continuous decline in battery storage capacity during charge–discharge cycles. Calculations of the energy cost in PV/wind/battery hybrid systems often omit the effects of battery degradation and the actual service life of the storage units. However, without an optimal combination of energy sources, such an HRES cannot provide effective solutions. Furthermore, managing HRESs that incorporate multiple REN sources is complex and requires robust optimization tools. Furthermore, sensitivity analysis is often limited or entirely omitted, even though uncertainties in input parameters—such as solar radiation, wind resources, or fuel price—can significantly alter the techno-economic feasibility of hybrid systems.

One of the most current applications of REN systems in agriculture is agrivoltaics. Agrivoltaic systems offer a significant opportunity to reconcile the competing land use demands of energy and agriculture. Among recent studies on agrivoltaics, the integration of photovoltaic systems into greenhouses stands out [78]. The shading effect and electricity generation potential of PV panels and semi-transparent PV films installed on greenhouse roofs vary depending on the type of greenhouse, roof design, and mounting configuration [79–81]. PV implementation on greenhouse roofs also influences crop selection due to the impact of shading [82].

1.3. Objectives of This Study

Through a series of optimization analyses, this study aims to establish the ideal hybrid system design—encompassing both grid-connected and off-grid scenarios—to power a greenhouse located in a rural area. This work systematically reviews previous research on the technical and economic feasibility of various hybrid power systems, identifying a critical gap in the lack of comprehensive comparative analyses of multiple configurations under consistent technical and economic assumptions. While prior studies have evaluated hybrid systems, such as diesel/PV, PV/wind, and standalone solar-wind systems, they frequently overlook factors such as battery degradation in cost calculations and typically

provide limited sensitivity analysis regarding uncertainties in input parameters such as solar irradiation and fuel prices. This study directly addresses these deficiencies by presenting a systematic comparison of diverse hybrid configurations for a greenhouse facility, including both grid-connected and off-grid scenarios. A key contribution is the inclusion of a detailed sensitivity analysis that specifically considers the potential impact of high inflation and interest rates on system costs. In addition to optimization, this study also employs sensitivity analyses to evaluate the effects of changes or uncertainties in model inputs, such as average wind speed, solar irradiation, and future fuel prices [83]. The findings, therefore, not only identify the most cost-effective and environmentally friendly configurations but also provide a robust framework for evaluating the trade-off between financial constraints and environmental goals in regions with similar climatic and economic conditions. The results demonstrate that the integration of photovoltaic and wind energy significantly reduces emissions by balancing environmental impact with cost-effectiveness. This reveals that although fully renewable systems are less economically viable, they are ideal for achieving the goal of carbon neutrality. The results obtained are at a level that can provide insights for countries with similar climate and economic conditions. The flowchart illustrating the methodology used in this study is presented in Figure 3.

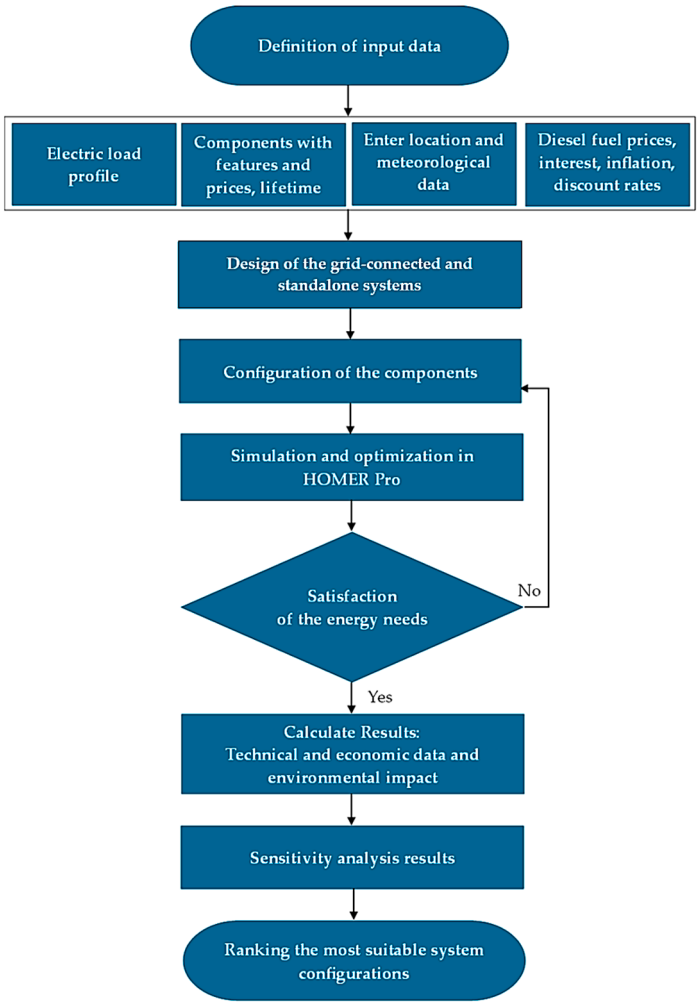


Figure 3. Flowchart.

2. Materials and Methods

2.1. Site and System Design Parameters

The greenhouse complex analyzed in this study is located in Sandıklı, Afyonkarahisar, Türkiye (38.45° N; 30.25° E) (Figure 4). The complex consists of an administrative building, a heating center, and a total greenhouse area of 7200 m^2. The greenhouse is covered with a plastic roof and polycarbonate (PC) panels on the sides. It is equipped with a thermal screen and utilizes geothermal energy for heating. The facility operates year-round, with uninterrupted production. It was proposed that the photovoltaic panels and wind turbines be installed on land situated to the north of the administrative building. The site was selected based on the absence of shading structures such as buildings, trees, or natural elevations, and the proximity to power transmission lines.

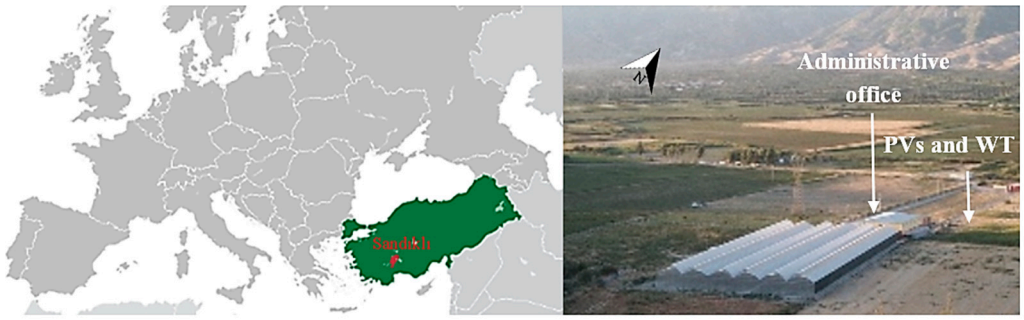


Figure 4. Map of Sandıklı and view of the area where the greenhouse is located at Sandıklı (Map: https://commons.wikimedia.org/wiki/File:Location_Turkey.svg (accessed on 12 May 2025), as modified by author).

This study was initiated with an analysis of the facility's daily electricity load profile and its annual variation to serve as the basis for energy system design. Regional data on daily solar irradiation, sunshine duration, temperature, and wind speed (Figure 5a–d) were obtained from the Surface Meteorology and Solar Energy database (NASA) [84] and were used to evaluate the REN potential of the area.

Simultaneously, the facility's electrical load distribution was determined by calculating the electricity consumed by ventilation, cooling, irrigation–fertilization, and heating systems, as well as the energy demand of the administrative offices. In these calculations, the rated power and daily operating hours of electrical machines and devices were considered (Equation (1)) [85], and energy consumption profiles were developed by comparing them with monthly electricity bills.

$$L_s = \sum_{n=1}^{N} Q_n P_n H_n \quad (1)$$

In this expression, L_S corresponds to the total energy demand (kWh), Q_n refers to the number of units, P_n specifies the rated capacity of each unit (kW), and H_n denotes the duration of operation (h).

The components utilized in the analysis of the proposed grid-connected and standalone systems (as detailed in Table 1) were carefully chosen based on the criteria of being both domestically produced and easily accessible. Using the optimization feature of the software, economic indicators such as the NPC and LCOE were obtained for the most suitable systems that could meet the facility's load.

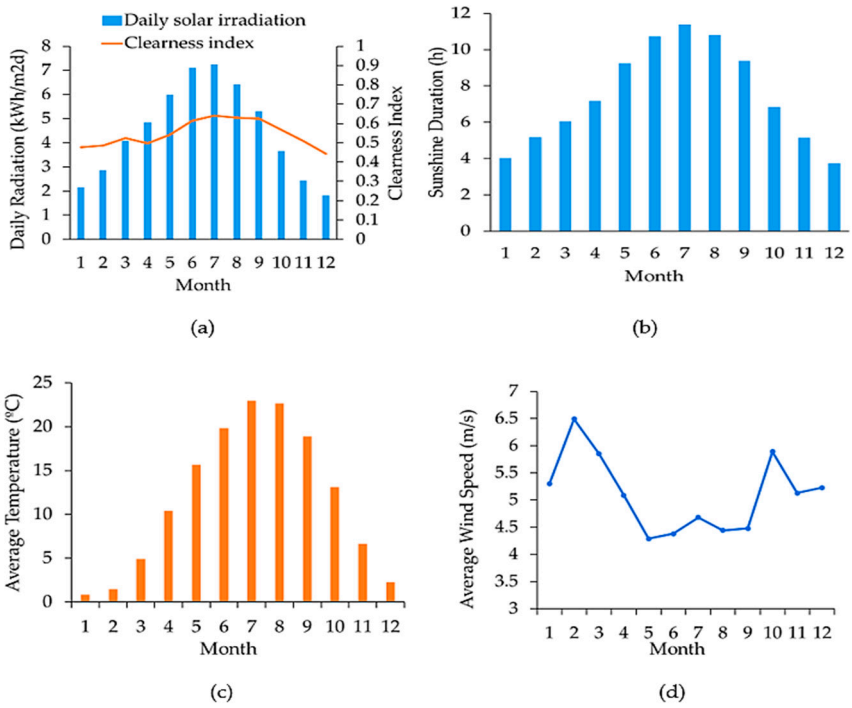


Figure 5. Daily solar irradiation and clearness index (**a**), sunshine duration (**b**), average temperature (**c**), and average wind speed (**d**).

Table 1. Technical specifications of the components.

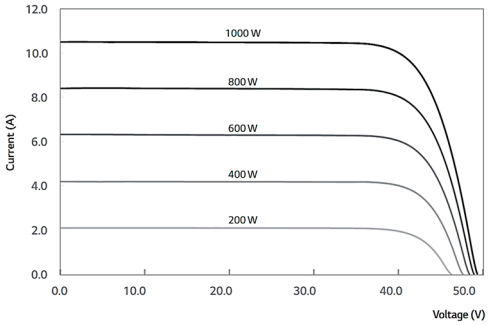
Component	Technical Specifications	
Panel (PV) 	Model: LG410N2W-V5 Rated capacity: 410 W Panel type: monocrystalline-Si Open circuit voltage (V_{oc}): 49.5 V Short circuit current (I_{sc}): 10.55 A Power tolerance: 0/3% Module efficiency: 19.8% Lifetime: 25 years	
Wind Turbine (WT) 	Model: Eocycle EOX S-16 Rated capacity: 30 kW Rotor diameter: 15.8 m Cut-in/out wind speed: 2.75/20 m/s Hub height: 23.8 m Lifetime: 30 years	Average wind speed (m/s) / Gross output (kWh/yr) 4.0 / 41,140 4.5 / 55,910 5.0 / 70,920 5.5 / 85,460 6.0 / 99,000 6.5 / 111,200 77.0 / 121,860 7.5 / 130,870

Table 1. *Cont.*

Component	Technical Specifications	
Inverter	Model: TommaTech Hybrid Rated capacity: 60 kW Rated AC output current: 87 A Grid connection form: 3-Phase Max. efficiency: 97.60 MPPT efficiency: >99% Lifetime: 15 years	
Generator (Gen)	Model: Generic Gen60 Fuel: Diesel Rated capacity: 60 kW Fuel curve intercept: 2.80 L/h Fuel curve slope: 0.253 L/h kW Minimum load ratio: 25% CO emission: 17.79 g/L Particulate matter: 0.0712 g/L Lifetime: 15,000 h	
Battery (B)	Model: SAFT/Kinetic 28S24M Chemistry: Li-ion Nominal voltage: 720 V Nominal capacity: 55 kWh Maximum capacity: 76.4 Ah Capacity Ratio: 0.927 Rate constant (1/h): 0.989 Roundtrip efficiency: 97% Maximum charge current: 82 A Maximum discharge current: 200 A Maximum charge rate: 1 A/Ah Initial state of charge: 100% Minimum state of charge: 5% Throughput: 240,000 kWh Lifetime: 20 years	

2.2. Mathematical Modeling of Energy Systems

2.2.1. HOMER Pro Software

The systems were technically and economically analyzed using HOMER Pro (ver.3.14.2). The software allows users to model and optimize a wide range of system configurations, including those that incorporate solar PV systems, wind turbines, batteries, diesel generators, and grid connections. The software also provides access to meteorological data for the simulation region. The operation of a hybrid microgrid can be simulated with time intervals ranging from one minute to one hour for an entire year [86].

2.2.2. Photovoltaic Systems

Photovoltaic modules function by converting incident solar radiation into direct current (DC) electricity via semiconductor materials. The conversion efficiency varies, with typical values ranging from 5% to 20% based on the specific cell configuration. Equation (2) can be used to calculate the power output of a PV array [86]:

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_P (T_c - T_{c,STC})] \quad (2)$$

In this context, Y_{PV} represents the total installed capacity of the PV array. The calculation also incorporates f_{PV}, the degradation factor; G_T, the solar irradiance on the PV surface [kW/m^2]; and $G_{T,STC}$, the irradiance under standard test conditions (1000 W/m^2).

Furthermore, the PV temperature coefficient, α_p [%/°C], along with the PV cell temperature, T_c, and the cell temperature under standard test conditions, $T_{c,STC}$ (25 °C), are also used.

2.2.3. Wind Turbine Systems

Wind turbines convert the kinetic energy of the wind into electrical energy using an alternator. The electricity generated is a function of multiple variables, such as the tower's height, the turbine's specific technical properties, the prevailing wind speed distribution, and the system's inherent energy conversion efficiency [87,88]. Equations (3) and (4) can be used to calculate the power generated by a turbine [89]:

$$P_{wt}(t) = \begin{cases} 0, \ v(t) \le v_{cut\text{-}in} \text{ or } v(t) \ge v_{cut\text{-}out} \\ P_r\left[\frac{v^3(t) - v^3_{cut\text{-}in}}{v_r^3 - v^3_{cut\text{-}in}}\right], \ v_r > v(t) > v_{cut\text{-}in} \\ P_r, \ v_{cut\text{-}in} \ge v(t) \ge v_r \end{cases} \quad (3)$$

In this study, P_r, v_r, $v_{cut\text{-}in}$, and $v_{cut\text{-}out}$ are used to denote the turbine's rated power, rated wind speed, and the lower and upper operational thresholds. Considering that wind velocity changes with altitude and measurement height, the turbine power output P_{wt} is derived from hub-height wind speed values [90].

$$v(t) = v_{ref}\left[\frac{H_{WT}}{H_{ref}}\right]^{\alpha} \quad (4)$$

where H_{ref}, the reference height, and H_{WT}, the turbine hub height, are pivotal parameters in wind energy calculations. The wind shear coefficient, α, typically ranges from 0.1 to 0.4 [91].

2.2.4. Diesel Generator Systems

A generator is an electric machine that converts mechanical energy into electrical energy using fossil fuels. The generator's efficiency increases logarithmically with output power. In diesel generators, the cost per kW is higher for lower-capacity units. Fuel consumption is calculated using Equation (5) [92]. In this study, the generator size was determined through optimization.

$$Fuelc._{DG} = (a \cdot T_{DG} + b \cdot P_{DG}) \quad (5)$$

Here, $Fuelc._{DG}$ denotes the diesel generator (DG) fuel consumption rate in liters per hour (L/h). The parameter a corresponds to the fuel intercept coefficient (L/kWh), taken as 0.0161 L/kWh at rated conditions. T_{DG} represents the generator's rated capacity in kilowatts (kW), while b represents the fuel slope (L/kWh), assigned a value of 0.2486 L/kWh of output. Finally, P_{DG} refers to the actual power output of the generator (kW).

2.2.5. Battery Storage

The battery bank, composed of series and parallel-connected batteries, functions as a backup system that maintains voltage stability throughout the load period. Equation (6) can be used to calculate battery capacity [92]:

$$C_{Batt} = \frac{E_L AD}{\eta_{inv} DOD \eta_{bat}} \quad (6)$$

In this formulation, E_L stands for the mean daily energy demand of the load (kWh/day), while AD indicates the number of days the system must operate independently without charging. The parameter η_{inv} represents the efficiency of the inverter, DOD speci-

fies the allowable depth of discharge of the battery, and η_{bat} corresponds to the efficiency of the battery storage unit.

2.2.6. Inverter

The inverter converts direct current from photovoltaic modules and battery storage into alternating current. This AC power meets the operational demands of electric motors, compressors, and pumps in the greenhouse facility. Inverter power is calculated using Equation (7) [93,94]. In this study, the inverter capacity was optimized as part of the hybrid system design.

$$P_{inv} = \frac{P_{peak}}{\eta_{inv}} \quad (7)$$

where P_{peak} corresponds to the aggregate peak power requirement of the system.

2.2.7. Grid (G)

The greenhouse operation holds a 150 kW electricity contract with a utility provider. Power is purchased based on an agricultural irrigation tariff. According to the Law on the Use of Renewable Energy Resources for Electricity Generation published by Türkiye's Energy Market Regulatory Authority (EMRA) [95], surplus energy from renewable systems can be sold, generating revenue for the operation. The costs of imported and exported electricity are offset. These energy tariffs are updated quarterly. For modeling purposes, the buy and sell prices set by the Energy Exchange Istanbul (EPIAS) for April–June 2025 are USD 0.096/kWh and USD 0.076/kWh, respectively [96].

2.3. Economic Analysis

2.3.1. The Net Present Cost (NPC)

Referred to as the life-cycle cost, the Net Present Cost (NPC) captures the present value of all expenditures required for installing and operating a component throughout the project period, offset against the present value of revenues generated in the same interval. Equation (8) [97] can be used to calculate the NPC:

$$NPC = \frac{R_t}{(1+i)^t} \quad (8)$$

In this equation, R_t represents the net cash inflow or outflow in a given period t. The term i is the discount rate, while t denotes the number of time periods. The real discount rate is used to convert between one-time costs and annualized costs. Equation (9) [98] can be used to calculate the actual discount rate:

$$i = \frac{i' - f}{1+f} \quad (9)$$

where i' is the nominal discount rate and f is the expected inflation rate. The discount rate of Türkiye was found to be 9.75 [99].

2.3.2. Levelized Cost of Energy (LCOE)

The Levelized Cost of Energy (LCOE) is a crucial metric for evaluating and comparing different energy generation technologies. It represents the average lifetime cost of electricity generation for a system, typically a hybrid one, expressed as a single value (e.g., USD/kWh).

This metric is calculated by dividing the total discounted lifetime costs of the system by its total discounted lifetime energy production. It provides a standardized method for comparing the cost-effectiveness of various energy systems over their entire operational lifespan, allowing for a more equitable assessment of different technologies (e.g., solar vs.

wind vs. diesel) with varying lifespans, capital costs, and operational expenses [100]. LCOE was calculated by Homer using the following Equation (10).

$$\text{LCOE} = \frac{C_{ann,tot}}{E_{served}} \quad (10)$$

where $C_{ann,tot}$ is the total annualized cost of the system (USD/yr) and E_{served} is the total annualized load served (kWh/yr).

3. Results

The electrical load distribution of the greenhouse is illustrated in Figure 6. The data show that the daily electricity consumption is 369.52 kWh, with a peak demand of 52.59 kW. The seasonal (Figure 7) and daily (Figure 8) load profiles of the greenhouse are presented below.

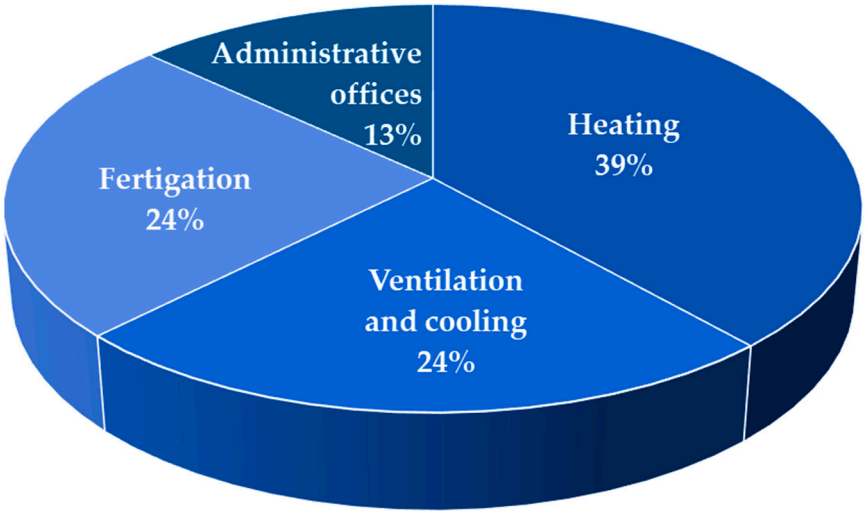


Figure 6. Electrical load distribution in the greenhouse.

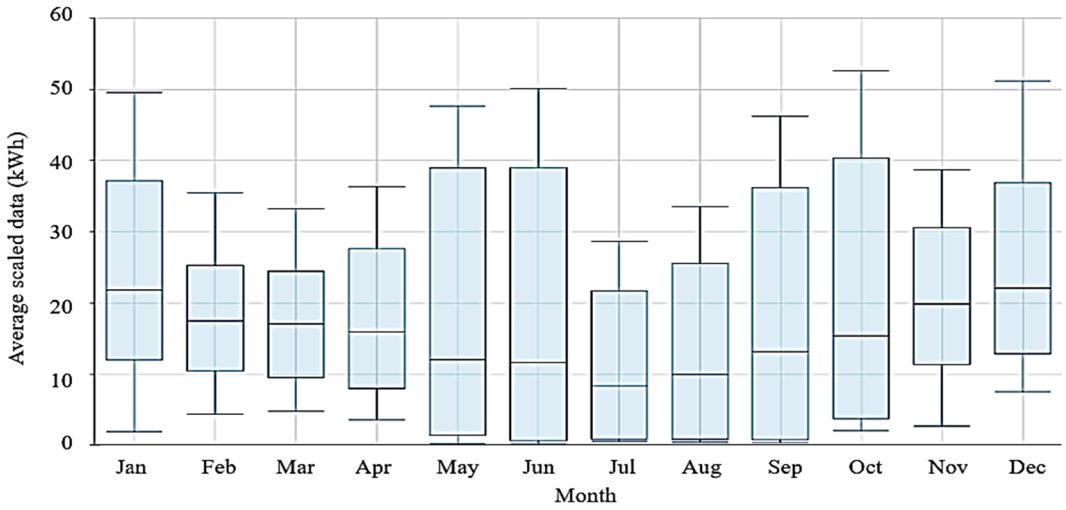


Figure 7. Scaled monthly average data.

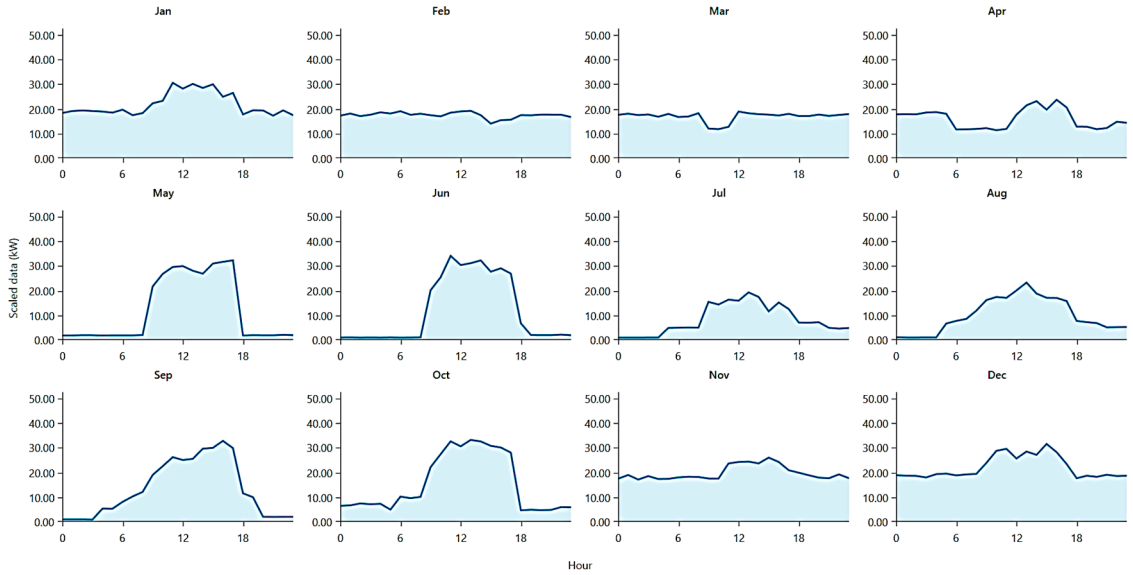


Figure 8. Scaled daily profile data.

The load profile presents daily and seasonal consumption data, ensuring that the proposed hybrid system aligns with the greenhouse's actual energy demand. This confirms the system's technical feasibility and suitability for reliably meeting the facility's operational energy needs.

During the optimization process, the objective was to maximize the Renewable Fraction (RF) and minimize LCOE, NPC, and emissions. The methodology offered a comprehensive framework that harmonized reliability, affordability, and environmental sustainability in energy access. To ensure adaptability to future uncertainties, sensitivity analyses were performed, considering varying inflation rates, fuel prices, solar radiation, and wind speeds under multiple scenarios. Additionally, the environmental impact (CO_2 emissions) was evaluated to balance cost and sustainability.

3.1. Analysis of Grid-Connected Systems

Table 2 presents a thorough comparison of six hybrid energy system configurations, analyzing their performance across economic, operational, and environmental metrics.

Table 2. Configuration of standalone systems with varying architectures.

Architecture	Cost				System		Grid	
	NPC (USD)	LCOE (USD/kWh)	Operating Cost (USD/yr)	Initial Capital (USD)	Renewable Fraction (%)	Reduction of CO_2 (%)	Energy Purchased (kWh)	Energy Sold (kWh)
G/PV	282,492	0.0401	4601	164,009	77.8	54.94	60,771	138,638
G/PV/WT	401,065	0.0542	5127	269,012	82.4	62.50	50,559	152,683
G/WT	445,910	0.1260	13,237	105,000	17.7	16.39	112,772	2152
G/PV/B	506,112	0.0718	10,954	224,013	77.8	54.94	60,771	138,642
G/PV/WT/B	624,729	0.0845	11,499	328,581	82.4	62.51	50,581	152,148
G/WT/B	785,724	0.2100	20,007	270,455	33.5	28.48	96,464	10,098

i. Economic Analysis: Among the examined configurations, [G/PV] was the most cost-effective design, with the lowest NPC (USD 282,492) and LCOE (USD 0.0401/kWh), and a moderate annual operating cost of USD 4601. However, systems such as [G/PV/WT/B], [G/PV/B], and [G/WT/B] incur higher NPCs (USD 624,729, USD 506,112, and USD 785,724, respectively) and higher LCOEs (USD 0.0845/kWh,

USD 0.0718/kWh, and USD 0.2100/kWh) due to heavy reliance on photovoltaic generation and battery storage. The [G/PV] and [G/PV/WT] configurations, with integrated PV components and low maintenance needs, offer the lowest operating costs (USD 4601 and USD 5127 per year, respectively). By contrast, the wind turbine-based [G/WT/B] system includes two turbines, resulting in a much higher annual operating cost (USD 20,007) due to the intensive maintenance requirements.

ii. Environmental Impact: [G/PV] was the most economically viable configuration, offering both low LCOE and substantial environmental benefits. Even though [G/PV/WT/B] requires higher investment, it achieves the highest CO_2 emission reductions, making it ideal for environmentally focused regions. However, its high initial capital cost may limit broader applicability. [G/PV/WT], which shares similar PV and WT components but excludes batteries, offers a cost-effective alternative with comparable emissions; in contrast, wind-dominated systems such as [G/WT] and [G/WT/B] fail to significantly reduce carbon emissions, rendering them less suitable for modern energy demands.

In addition to offering CO_2 emission reduction effects of 62.50% for the [G/PV/WT] configuration and 54.94% for the [G/PV] system, these hybrid systems provide versatile solutions for various energy demands by balancing both economic and environmental objectives. The [G/PV] and [G/PV/WT] configurations stand out as prominent hybrid alternatives due to their low NPC, competitive LCOE, and significant emission reductions. They are ideal for projects that aim to integrate cost-efficiency with environmental impact mitigation. On the other hand, while [G/PV/B] and [G/PV/WT/B] offer comparable emission reduction benefits (54.94% and 62.51%, respectively), their high NPC and LCOE values may limit their applicability in regions with limited budgets. Other alternative systems, such as [G/WT] and [G/WT/B], perform poorly across all evaluation criteria due to their high emissions and operating costs, which makes them unsuitable for future energy needs.

Ultimately, the [G/PV] configuration was determined to be the most optimal overall in terms of cost, reliability, and moderate emission reductions. Aside from this system, the [G/PV/WT] setup is also considered acceptable. Even though [G/PV/B] and [G/PV/WT/B] are ideal in terms of emissions, they require significantly higher investment. The [G/WT] and [G/WT/B] systems are the least favorable in terms of environmental benefits, with emission reductions of only 16.39% and 28.48%, respectively. Given their high costs, emissions, and inefficiency, the use of [G/WT] and [G/WT/B] systems is strongly discouraged.

Figure 9 illustrates two grid-connected energy system configurations for greenhouses, labeled (a) and (b). These systems are designed to meet an energy demand of 369.52 kWh/d, with a 52.59 kW peak load.

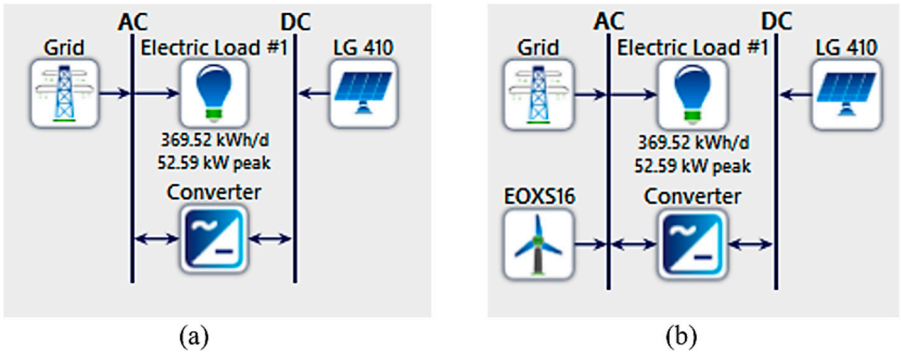


Figure 9. Design of grid-connected [G/PV] (**a**) and [G/PV/WT] (**b**) systems.

a. [G/PV] system: The grid is the primary energy source, and PV panels supply additional energy and export any surplus solar generation back to the grid. Due to its low maintenance requirements, this system has the lowest operating costs. Its lifespan corresponds to that of the PV panels. One challenge, however, is that the system's performance is dependent on daily solar irradiation and sunlight availability.
b. Environmental Impact: [G/PV] was the most economically viable configuration, offering both low LCOE and substantial environmental benefits. Even though [G/PV/WT/B] requires higher investment, it offers the highest CO_2 emission reductions, making it ideal for environmentally focused regions. However, its high initial capital cost may limit broader applicability. [G/PV/WT], which shares similar PV and WT components but excludes batteries, presents a cost-effective alternative with comparable emissions. In contrast, wind-dominated systems such as [G/WT] and [G/WT/B] fail to significantly reduce carbon emissions, rendering them less suitable for modern energy demands.

Table 3 provides a detailed cost breakdown of the proposed hybrid energy system over its lifetime, including capital investment, component replacements, operation and maintenance (O&M), fuel, and salvage values.

Table 3. Cost evaluation of grid-connected [G/PV] system components.

Component	Capital (USD)	Replacement (USD)	O&M (USD)	Salvage (USD)	Total (USD)
Grid (G)	0.00	0.00	−121,107.18	0.00	−121,107.18
Panel (PV)	153,414.63	0.00	232,414.04	0.00	385,828.68
Inverter	10,594.35	9672.50	802.49	−3298.37	17,770.97
System	164,008.98	9672.50	112,109.35	−3298.37	282,492.47

Among the components, the PV panel system requires the highest initial investment at USD 153,414.63, with the total cost over its 25-year lifespan reaching USD 385,828.68. In contrast, the inverter is the most economical component, with an initial cost of USD 10,594.35. The total system costs USD 282,492.47, the majority of which arises from operation and maintenance expenses (USD 112,109.35). As the PV panels and the overall system have the same lifespan, their salvage value is excluded from the total; therefore, the system's total salvage value of USD 3298.37 pertains solely to the inverter.

The annual energy demand of the greenhouse complex is 134,875 kWh, with a daily average consumption of 369.52 kWh. The proposed [G/PV] system can adequately meet this requirement and even generate surplus energy that can be sold back to the grid. The PV panels produce 224,311 kWh annually, of which 138,638 kWh is surplus energy sold to the grid (Table 4, Figures 10 and 11a). Conversely, 60,771 kWh of electricity is purchased from the grid each year (Figure 11b). Consequently, 78.7% of the greenhouse's annual energy demand is met by the PV system, while 21.3% is supplied by the grid. The total annual CO_2 emissions amount to 38,408 kg.

An examination of Figure 11b reveals that minimal energy is drawn from the grid during the summer night hours. This is directly correlated with the high solar energy production during the day. As a pure [G/PV] system, the high solar irradiance during the summer months (Figure 5a) allows the system to generate a significant surplus of electricity. This surplus is transferred back to the grid, creating a revenue stream that offsets the cost of the energy consumed. This finding is further corroborated by the net energy figures in Table 4, which demonstrate that from April to October, the system consistently sells more energy than it purchases, resulting in a negative net cost for the greenhouse.

In essence, the system's primary objective is to maximize the on-site utilization of free solar energy. During daylight hours, the high PV output not only meets the facility's needs but also generates a substantial surplus. The net financial benefit derived from selling this surplus renders the active purchase of additional energy at night economically unnecessary. The model is optimized for cost-effectiveness, and during the summer months, this is achieved by harnessing the abundant solar resources rather than purchasing from the grid.

Table 4. Grid demand and rate schedule.

Month	Energy Purchased (kWh)	Energy Sold (kWh)	Net Energy Purchased (kWh)	Peak Load (kW)	Energy Charge (USD)	Demand Charge (USD)
January	10,612	3828	6784	41	727.78	0
February	7469	6528	940	33	220.85	0
March	7430	11,538	−4109	33	−163.69	0
April	5841	12,886	−7045	30	−418.62	0
May	1022	15,568	−14,546	34	−1085.08	0
June	590	18,753	−18,162	23	−1368.51	0
July	988	22,821	−21,833	10	−1639.57	0
August	1299	19,022	−17,723	11	−1320.93	0
September	1665	12,860	−11,195	30	−817.55	0
October	3511	7095	−3583	34	−202.12	0
November	9176	5191	3985	32	486.4	0
December	11,169	2548	8621	38	878.58	0
Annual	60,771	138,638	−77,866	41	−4702.46	0

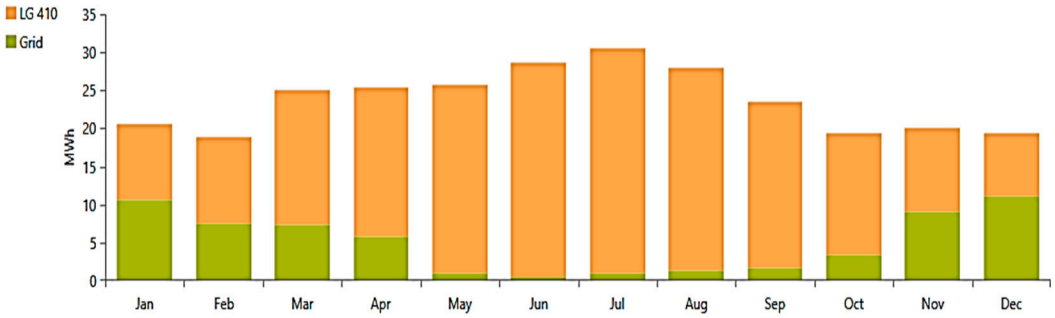


Figure 10. Comparison of energy sold to the grid by PV vs. energy purchased from the grid.

Sensitivity Analysis for Grid-Connected Systems

In the sensitivity analysis conducted for the proposed grid-connected [G/PV] system, three different scenarios (minimum, average, and maximum) were evaluated across five key parameters (Table 5). Given the lowest, average, and highest input values, the payback periods were calculated to be 12, 2.8, and 25 years, respectively (Figure 12). These findings indicate that the payback period for the proposed grid-connected system is minimized under average parameter conditions.

In Türkiye, the electricity purchase and sellback prices from and to the grid, as announced by EPIAS for the April–June 2025 period, are USD 0.096/kWh and USD 0.076/kWh, respectively. In addition to these base rates, four alternative scenarios were developed, and the corresponding cost and economic outcomes were analyzed. The results obtained are presented in Table 6. The region's average solar irradiance and temperature data were used for the sensitivity analyses. Values for NPC, LCOE, IRR, and payback periods were determined based on variations in power price, sellback rate, and expected inflation. As seen in Table 6, under the assumptions of a power purchase price

of USD 0.16/kWh, a sellback price of USD 1.18/kWh, and inflation rates of 5% and 10%, the shortest payback period was found to be 2.1 years. Moreover, the highest expected IRR value (47%) was achieved under these conditions. On the other hand, under the assumption of a 30% inflation rate, both the payback period and IRR performance became uncertain, indicating that the system would remain in debt throughout its operational lifespan. Elevated inflation adversely impacts the investment's profitability. If the inflation rate remains at or below 5%, a significant improvement in profitability can be realized.

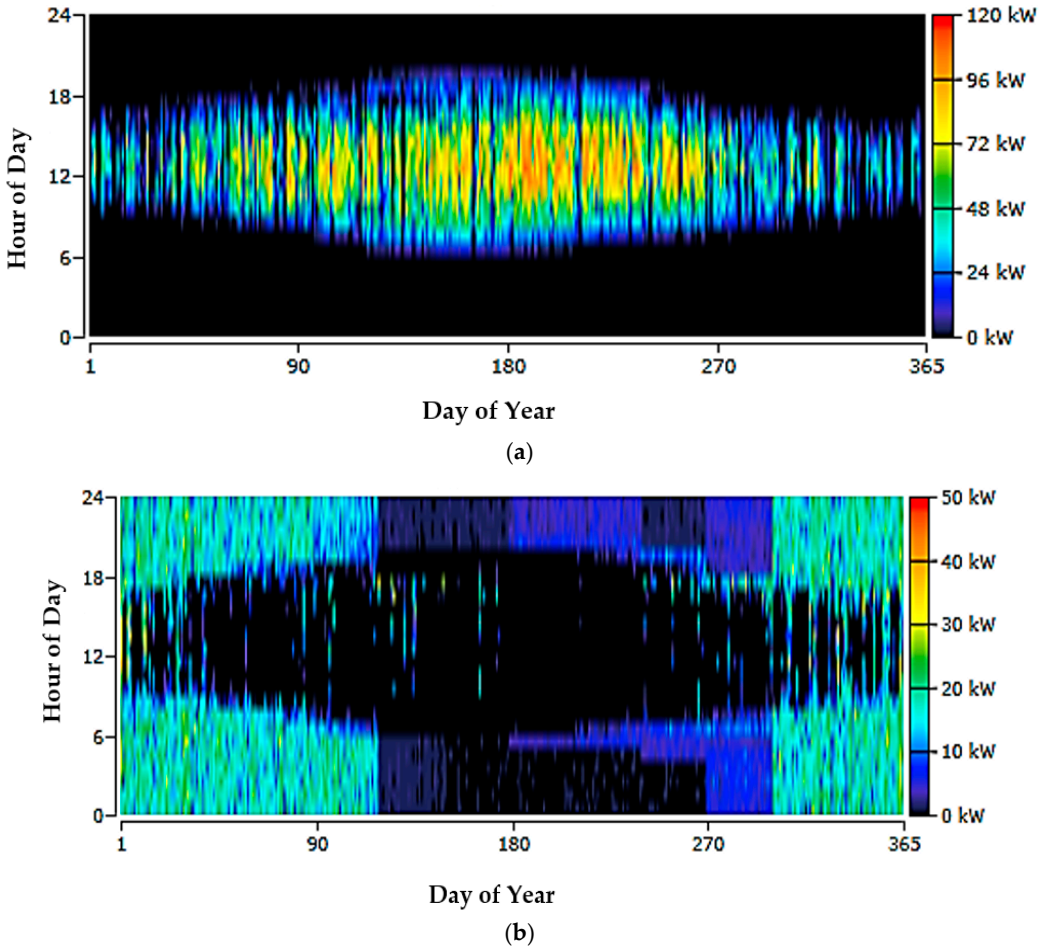


Figure 11. Energy sold to the grid (**a**) and energy purchased from the grid (**b**).

Table 5. Sensitivity inputs (for the winning system architecture, [G/PV]).

Parameter	Minimum	Average	Maximum
Solar scaled average (kWh/m.d)	2.0	4.5	7.0
Temperature scaled average (°C)	1.0	11.5	25.0
Expected inflation rate (%)	5	10	30
Grid power price (USD/kWh)	0.12	0.14	0.16
Grid sellback rate (USD/kWh)	0.10	0.14	0.18

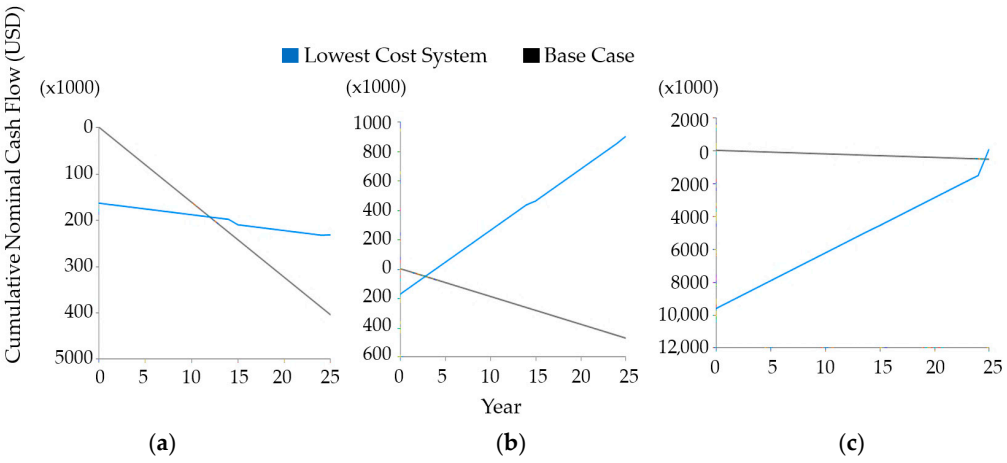


Figure 12. Cash flow and payback period of the [G/PV] system based on minimum (**a**), average (**b**), and maximum (**c**) sensitivity parameters.

Table 6. Cost and economic performance metrics under different scenarios (power price, sellback rate, expected inflation).

Power Price (USD/kWh)	Sellback Rate (USD/kWh)	Expected Inflation Rate (%)	NPC (USD)	LCOE (USD/kWh)	IRR (%)	Simple Payback (yr)
0.10	0.8	5	191,525	0.0960	18	5.5
		10	333,462	0.0960	18	5.5
		30	5.65 M	0.0960	-	25<
	0.10	5	191,525	0.0960	24	4.2
		10	333,462	0.0960	24	4.2
		30	5.65 M	0.0960	-	25<
	0.14	5	191,525	0.0960	34	3.0
		10	333,462	0.0960	34	3.0
		30	5.65 M	0.0960	-	25<
	0.18	5	191,525	0.0960	44	2.3
		10	333,462	0.0960	44	2.3
		30	5.65 M	0.0960	-	25<
0.12	0.8	5	239,407	0.120	19	5.2
		10	416,827	0.120	19	5.2
		30	7.06 M	0.120	-	25<
	0.10	5	239,407	0.120	25	4.0
		10	416,827	0.120	25	4.0
		30	7.06 M	0.120	-	25<
	0.14	5	239,407	0.120	35	2.9
		10	416,827	0.120	35	2.9
		30	7.06 M	0.120	-	25<
	0.18	5	239,407	0.120	45	2.2
		10	416,827	0.120	45	2.2
		30	7.06 M	0.120	-	25<
0.14	0.8	5	279,308	0.140	20	5
		10	486,298	0.140	20	5
		30	8.24 M	0.140	-	25<
	0.10	5	279,308	0.140	26	3.8
		10	486,298	0.140	26	3.8
		30	8.24 M	0.140	-	25<
	0.14	5	279,308	0.140	36	2.8
		10	486,298	0.140	36	2.8
		30	8.24 M	0.140	-	25<
	0.18	5	279,308	0.140	46	2.2
		10	486,298	0.140	46	2.2
		30	8.24 M	0.140	0.033	25

Table 6. *Cont.*

Power Price (USD/kWh)	Sellback Rate (USD/kWh)	Expected Inflation Rate (%)	NPC (USD)	LCOE (USD/kWh)	IRR (%)	Simple Payback (yr)
0.16	0.8	5	319,209	0.160	21	4.8
		10	555,769	0.160	21	4.8
		30	9.41 M	0.160	-	25<
	0.10	5	319,209	0.160	27	3.7
		10	555,769	0.160	27	3.7
		30	9.41 M	0.160	-	25<
	0.14	5	319,209	0.160	37	2.7
		10	555,769	0.160	37	2.7
		30	9.41 M	0.160	-	25<
	0.18	5	319,209	0.160	47	2.1
		10	555,769	0.160	47	2.1
		30	9.41 M	0.160	0.069	25

3.2. Standalone Systems

i. Economic Analysis: The cost of the most economical configuration, [Gen/PV/B] (USD 1.19 million), is approximately three times lower than the most expensive system, [WT/B] (USD 4.52 million). The significantly higher cost of the [WT/B] system stems from its reliance on 12 wind turbines. Generator-based systems such as [Gen/PV] and [Gen/PV/WT] (USD 1.85 million and USD 1.92 million, respectively) fall into the mid-range cost category; however, their environmental benefits are notably limited.

From the perspective of energy production cost, the system with the lowest LCOE is [Gen/PV/B], with a value of 0.342 USD/kWh. In contrast, even though it is designed to achieve zero emissions, the [WT/B] system has the highest LCOE at 1.370 USD/kWh due to its high capital investment requirements. This underscores the inevitable trade-off between environmental sustainability and financial feasibility (Table 7).

On the other hand, PV-integrated configurations such as [Gen/PV/B] and [Gen/PV/WT/B] offer the lowest operational costs, attributed to their low fuel consumption (20,363 L/year and 17,574 L/year, respectively) and reduced maintenance needs (USD 39,321 and USD 37,155, respectively). On the other hand, the [WT/B] system has the highest operational cost (USD 100,917) due to the substantial maintenance requirements of its 12 wind turbines.

ii. Environmental Impact: Configurations such as [Gen/PV/B] and [Gen/PV/WT/B], which provide both low LCOE and considerable environmental benefits, emerge as the most cost-effective alternatives. Despite their higher financial costs, the [PV/WT/B], [PV/B], and [WT/B] systems represent more suitable options for regions prioritizing environmental sustainability thanks to their zero-emission advantages. However, the substantial capital investments required by these systems may limit widespread adoption. However, generator-based systems such as [Gen], [Gen/PV], [Gen/WT], and [Gen/PV/WT] fail to yield meaningful reductions in carbon emissions, which makes them inadequate for meeting contemporary energy demands.

The [Gen/PV/B] system offers a balanced solution, achieving a 64.58% reduction in CO_2 emissions. Similarly, [Gen/PV/WT/B] and [Gen/WT/B] provide slightly lower yet comparable environmental benefits, with reductions of 69.43% and 45.30%, respectively. These hybrid systems balance economic and environmental objectives, offering versatile solutions for different energy requirements. In particular, [Gen/PV/B] and [Gen/PV/WT/B] emerge as optimal hybrid configurations due to their low NPC, competitive LCOE, and sig-

nificant emissions reductions, making them ideal for projects seeking both cost-effectiveness and environmental performance.

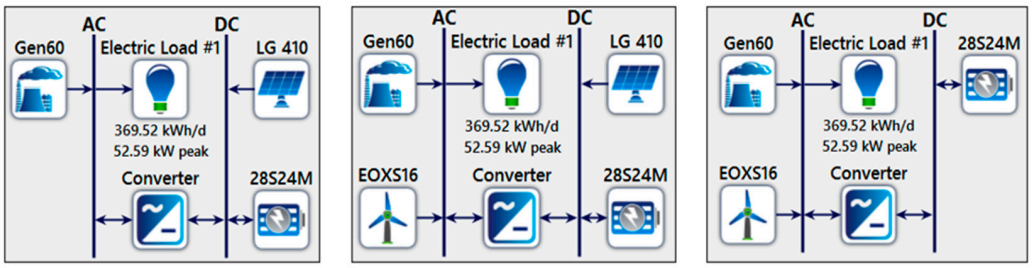
Table 7. System configuration of the standalone energy system.

Architecture		Cost				System		
System Type	**System Configuration**	**NPC (USD)**	**LCOE (USD/kWh)**	**Operating Cost (USD/yr)**	**Initial Capital (USD)**	**Renewable Fraction (%)**	**Total Fuel (L/yr)**	**Reduction of CO_2 (%)**
Standalone	Gen/PV/B	1.19 M	0.342	39,321	173,909	56.8	20,363	64.58
	Gen/PV/WT/B	1.22 M	0.350	37,155	258,453	63.1	17,574	69.43
	Gen/WT/B	1.65 M	0.476	53,245	283,459	32.4	31,449	45.30
	Gen/PV	1.85 M	0.531	69,871	46,672	0	52,209	9.19
	Gen/PV/WT	1.92 M	0.553	69,032	143,441	0	49,886	13.23
	Gen	1.92 M	0.554	74,252	11,500	0	57,493	0
	Gen/WT	1.96 M	0.566	71,749	116,500	0	53,402	7.12
	PV/WT/B	2.54 M	0.759	58,950	1.02 M	100	0	100
	PV/B	2.80 M	0.837	74,327	883,702	100	0	100
	WT/B	4.52 M	1.370	100,917	1.93 M	100	0	100

While [PV/WT/B], [PV/B], and [WT/B] systems offer the advantage of zero emissions, their high NPC and LCOE values may limit their feasibility in budget-constrained regions. Generator-based systems such as [Gen/PV], [Gen/PV/WT], [Gen], and [Gen/WT] perform poorly across all assessment criteria due to high emissions and operating costs, and are thus considered unsuitable for addressing future energy needs.

In conclusion, the [Gen/PV/B] configuration is recommended as the most viable option due to its low cost, reliability, and emissions reduction. The second and third preferred options are [Gen/PV/WT/B] and [Gen/WT/B], respectively. While [PV/WT/B], [PV/B], and [WT/B] are ideal for achieving carbon neutrality, they require substantially higher budgets. Due to their high costs, emissions, and inefficiency, the [Gen/PV], [Gen/PV/WT], [Gen], and [Gen/WT] systems should be avoided.

Figure 13 depicts three alternative configurations of the greenhouse energy system, identified as (a), (b), and (c), designed to cover a daily demand of 369.52 kWh and a peak load of 52.59 kW.



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

Figure 13. Proposed off-grid systems: [Gen/PV/B] (**a**), [Gen/PV/WT/B] (**b**), [Gen/WT/B] (**c**).

a. [Gen/PV/B] system: The system is primarily powered by the generator, with solar PV offering additional supply. Surplus solar energy is directed to the battery, and a inverter facilitates AC–DC conversion to decrease diesel usage. Despite these features, challenges persist, notably the dependence on diesel, relatively high operating costs, and constrained storage capacity.
b. [Gen/PV/WT/B] system: This hybrid system integrates wind generation to complement solar PV and reduce diesel dependency, particularly during nighttime or

low-sunlight conditions. The generator ensures supply during peak load events. Key advantages include enhanced system reliability, reduced operational costs, and minimized environmental impact; however, it requires sophisticated control systems and is sensitive to local wind conditions.

c. [Gen/WT/B] system: As illustrated in Figure 13c, this configuration combines a diesel generator, wind turbine, inverter, and battery. The turbine decreases fuel consumption, while the generator compensates for reduced wind availability. Benefits include fuel economy and improved environmental performance, although challenges stem from intermittent wind resources and constrained battery storage.

The [Gen/PV/B] configuration emerges as the most cost-effective design, with the lowest NPC of USD 1.19 million and an LCOE of USD 0.342/kWh. It also maintains a reasonable annual operating cost of USD 39,321. In contrast, the [PV/WT/B], [PV/B], and [WT/B] systems incur significantly higher costs (USD 2.54 million, USD 2.80 million, and USD 4.52 million in NPC, and USD 0.759/kWh, USD 0.836/kWh, and USD 1.370/kWh in LCOE, respectively) primarily due to their heavy reliance on photovoltaic generation and battery storage. The [WT/B] system, in particular, has the highest operating expenses (USD 100,917/year), largely attributed to the maintenance demands of its 12 wind turbines, as well as high upfront costs.

Generator-based systems create considerably higher operational expenses due to elevated fuel consumption and frequent maintenance requirements. From an environmental perspective, the [PV/WT/B], [PV/B], and [WT/B] systems offer the best performance, producing zero CO_2 emissions. Even though they demand high initial capital investment, they are viable options for projects prioritizing sustainability.

However, the generator-only system has the highest environmental impact, with annual CO_2 emissions of 150,377 kg, making it the least eco-friendly option. The [Gen/PV/WT/B] and [Gen/PV/B] systems achieve CO_2 emission reductions of 69.43% and 64.58%, respectively. These findings align with those reported by Woldegiyorgis et al. [101], Samatar et al. [102], and Eze et al. [103], indicating a balanced approach among cost-effectiveness, reliability, and environmental benefits.

Table 8 presents a detailed lifetime cost breakdown of the proposed hybrid energy system, including capital, replacement, operation and maintenance (O&M), fuel, and salvage values.

Table 8. Cost evaluation of the components of the standalone [Gen/PV/B] hybrid system.

Component	Capital (USD)	Replacement (USD)	O&M (USD)	Fuel (USD)	Salvage (-) (USD)	Total (USD)
Generator (Gen)	11,500.00	47,430.39	2592.14	629,308.62	3976.55	686,854.60
Panel (PV)	97,697.78	0.00	148,006.33	0.00	0.00	245,704.11
Battery (B)	60,000.00	37,121.02	154,523.93	0.00	5525.37	246,119.59
Inverter	4710.96	4301.04	356.84	0.00	1466.68	7902.16
System	173,908.74	88,852.46	305,479.24	629,308.62	10,968.59	1,186,580.46

The generator (Gen) emerges as the most expensive system component, with a total cost of USD 686,854.60. This figure is predominantly driven by high fuel expenses (USD 629,308.62) and replacement costs (USD 47,430.39), partially offset by a USD 3976.55 salvage value. The photovoltaic (PV) system requires the highest initial investment at USD 97,697.78, resulting in a total lifecycle cost of USD 245,704.11 over a 25-year period. The lithium-ion battery system, despite zero fuel costs, has high initial (USD 60,000) and replacement (USD 37,121.02) expenses, along with a USD 5525.37 salvage value, totaling USD 246,119.59. The inverter, at USD 7902.16, is the most cost-efficient component.

The system's total cost amounts to USD 1186,580.46, with the bulk attributed to generator fuel (USD 629,308.62) and O&M costs (USD 305,479.24). While diesel enhances system reliability, it increases operational expenditures. In contrast, solar power requires higher upfront capital but benefits from lower operating costs. The USD 10,968.59 salvage value reflects long-term financial offsets. For optimal cost-effectiveness, a balanced investment in REN technologies and conventional systems is essential.

The greenhouse complex has an annual energy demand of 134,875 kWh, translating to an average daily consumption of 369.52 kWh. The proposed hybrid systems easily meet this demand, with annual outputs of 201,092 kWh ([Gen/PV/B]), 187,092 kWh ([Gen/PV/WT/B]), and 139,723 kWh ([Gen/WT/B]).

The [Gen/PV/B] system generates 201,092 kWh annually, with 71.1% supplied by PV and the remaining 28.9% by the generator (Figure 14). Generator activity is most pronounced during winter months, when solar irradiance is minimal. Conversely, its operation is lowest from late May through mid-August, with projected fuel consumption ranging from 2 to 4 L/h and an average electrical output of 17.3 kW during this period (Figure 15a,b). The generator is expected to operate for 3355 h annually, consuming approximately 20,362 L of fuel.

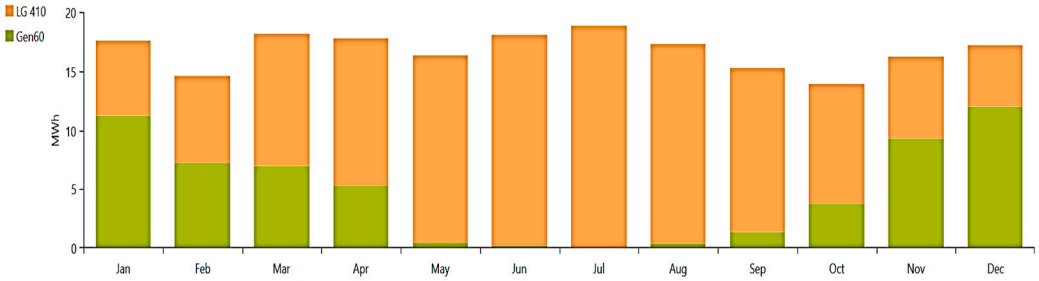


Figure 14. Energy production by the PV and the generator.

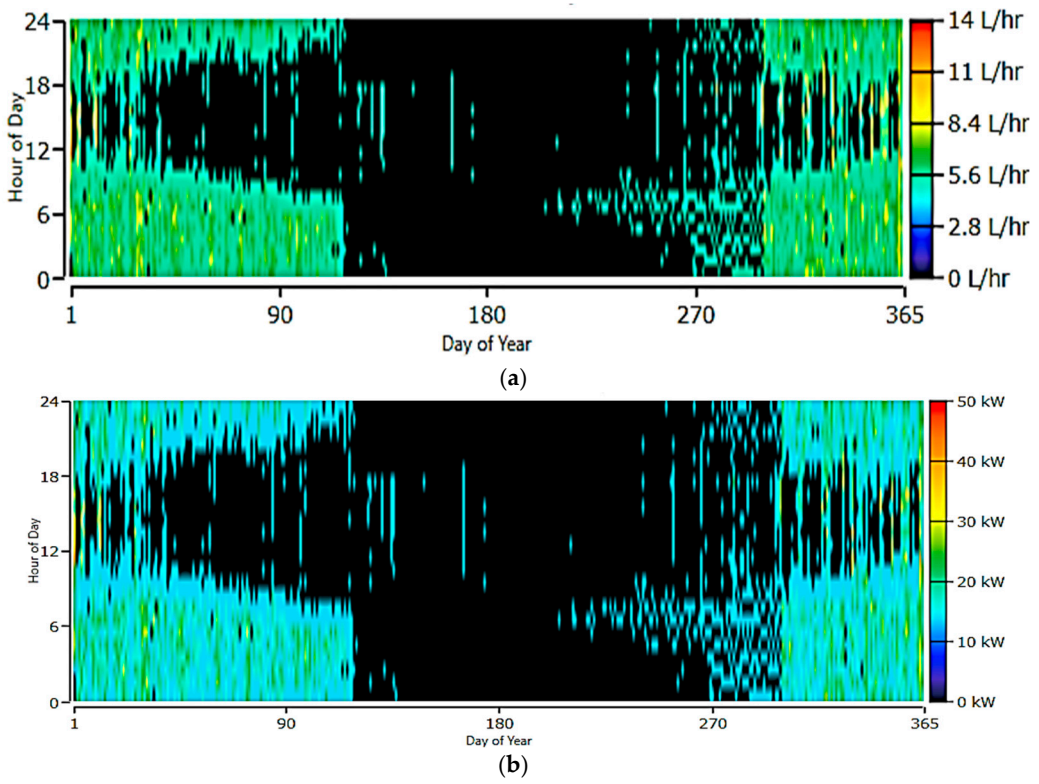


Figure 15. Annual generator fuel consumption (**a**) and power output (**b**).

Most systems generate excess electricity ranging from 2309 to 441,390 kWh while maintaining zero unmet load, ensuring robust storage capacity. Even the smallest energy surplus contributes to reliable energy buffering. However, three systems ([PV/WT/B], [PV/B], and [WT/B]) display minor annual unmet loads of 4922 kWh, 5007 kWh, and 6179 kWh, respectively. These deficiencies are not due to production limitations but rather temporary inefficiencies in storage or distribution. Overall, the proposed hybrid systems not only satisfy the greenhouse's energy needs but also support reliable electrification and surplus generation.

Hybrid systems combining PV, wind turbines (WT), diesel generators, and battery storage offer economically and environmentally balanced solutions. With REN shares ranging from 32.4% to 63.1%, LCOE between USD 0.342 and USD 0.476/kWh, and NPC between USD 1.19 million and USD 1.22 million, they represent the most cost-efficient options. Although these systems require higher initial capital investments (USD 173,909 to USD 283,459) compared with diesel-only alternatives, they benefit from lower annual operational costs (USD 37,155 to USD 53,245) and significantly reduced CO_2 emissions (45,966 to 82,256 kg/year). These advantages render hybrid systems not only economically viable but also environmentally sustainable, making them ideal solutions for off-grid applications. These findings are consistent with those reported by Woldegiyorgis et al. [101] and Kumar et al. [104].

In contrast, diesel-only systems require lower initial investments (USD 11,500 to USD 283,459), but pose long-term challenges, such as higher LCOE (USD 0.476 to USD 0.566/kWh), increased NPC (USD 1.85 million to USD 1.96 million), higher annual O&M costs (USD 53,245 to USD 74,252), and substantial CO_2 emissions (136,556 to 150,377 kg/year). Even though fully renewable systems emit no CO_2, their high capital costs (USD 883,702 to USD 1.93 million) and elevated NPC values (USD 2.80 million to USD 4.52 million) limit their feasibility. Despite their lower O&M costs (USD 74,327 to USD 100,917/year), their economic viability depends heavily on cost parameters. Factors such as component prices and discount rates significantly influence the feasibility of these systems. Lower financing costs could substantially enhance the applicability of both hybrid and renewable configurations.

Sensitivity Analysis for Standalone Systems

A sensitivity analysis of the proposed standalone [Gen/PV/B] system was conducted based on four parameters under three scenarios (minimum, average, and maximum values) (Table 9). The resulting payback periods were found to be 3.9, 2.4, and 5.1 years, respectively (Figure 16a–c). These outcomes indicate that the system achieves the shortest payback period under average parameter conditions.

Table 9. Sensitivity inputs (for the winning system architecture, [Gen/PV/B]).

Parameter	Minimum	Average	Maximum
Solar scaled average (kWh/m.d)	2.0	4.5	7.0
Temperature scaled average (°C)	1.0	11.5	25.0
Diesel fuel price (USD/L)	1.2	1.5	1.8
Expected inflation rate (%)	5	10	30

In addition, Table 10 presents a comprehensive analysis of the NPC, LCOE, IRR, and payback period, considering the average climatic conditions (solar radiation, temperature, and wind speed) at the greenhouse site, alongside different economic parameters such as power price, sellback rate, and expected inflation rate. The sensitivity analysis was conducted using the average climate conditions of the greenhouse location, evaluating various energy purchase rates from the grid (USD 0.10, USD 0.12, USD 0.14, and USD 0.16/kWh)

and energy sellback prices to the grid (USD 0.08, USD 0.10, USD 0.14, and USD 0.18/kWh), and examining the resulting costs and economic indicators.

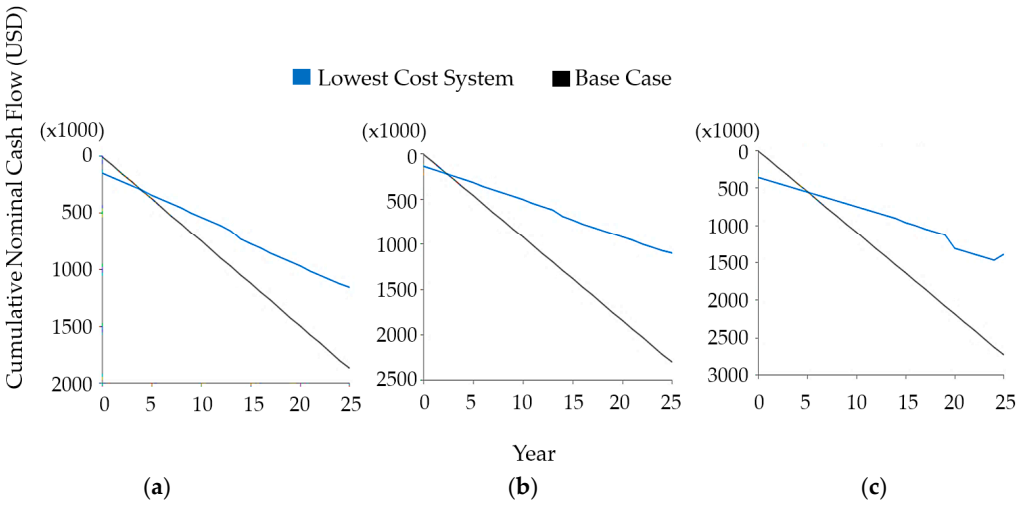


Figure 16. Cash flow and payback period for the [Gen/PV/B] system under minimum (**a**), average (**b**), and maximum (**c**) sensitivity variables.

Table 10. Economic indicators and costs under different scenarios.

Solar Energy (kWh/m^2·d)	Fuel Price (USD/L)	Expected Inflation Rate (%)	NPC (USD)	LCOE (USD/kWh)	IRR (%)	Simple Payback (yr)
2.0	1.2	5	1.11 M	0.557	24	4.0
		10	1.92 M	0.554	21	4.7
		30	32.0 M	0.545	12	7.8
	1.5	5	1.37 M	0.685	28	3.5
		10	2.37 M	0.682	26	3.7
		30	39.6 M	0.673	16	6.1
	1.8	5	1.62 M	0.813	33	3.0
		10	2.81 M	0.810	32	3.1
		30	47.1 M	0.800	15	6.2
4.5	1.2	5	1.11 M	0.557	35	2.8
		10	1.92 M	0.554	32	3.1
		30	32.0 M	0.545	18	5.4
	1.5	5	1.37 M	0.685	42	2.3
		10	2.37 M	0.682	41	2.4
		30	39.6 M	0.673	23	4.3
	1.8	5	1.62 M	0.813	50	1.9
		10	2.81 M	0.810	48	2.1
		30	47.1 M	0.800	17	5.8
7.0	1.2	5	1.11 M	0.557	40	2.5
		10	1.92 M	0.554	38	2.6
		30	32.0 M	0.545	21	4.6
	1.5	5	1.37 M	0.685	50	1.9
		10	2.37 M	0.682	49	2.0
		30	39.6 M	0.673	20	4.9
	1.8	5	1.62 M	0.813	60	1.7
		10	2.81 M	0.810	55	1.8
		30	47.1 M	0.800	19	5.1

As shown in Table 10, the shortest payback period (ranging from 1.7 to 2.0 years) was observed under conditions of the highest solar irradiance (7.0 kWh/m^2/day) and the lowest inflation rates (5% and 10%). Notably, the highest expected IRR, ranging between 49% and 60%, was also achieved under these conditions. This rate is approximately 13% higher than that observed for the grid-connected system. Conversely, the longest payback period, ranging between 4 and 8 years, was found under high inflation conditions (30%). As expected, the poorest IRR performance, varying between 12% and 23%, also occurred under these high-inflation scenarios. Although high inflation adversely affects investment profitability, this negative impact appears to be more predictable compared with grid-connected systems. If inflation remains at or below 5%, the standalone system, like the grid-connected one, is projected to be financially viable.

4. Discussion

The study's outcomes reveal the inherent tension between achieving economic feasibility and ensuring environmental sustainability in the configuration of hybrid energy systems for greenhouses. For grid-connected scenarios, the [G/PV] configuration emerged as the most economically attractive option, with the lowest NPC and LCOE (Table 2), while still delivering a 54.94% reduction in CO_2 emissions. The system's capacity to generate surplus electricity, illustrated in Figures 10 and 11, highlights its dual role in meeting the greenhouse's internal demand and generating additional revenue through grid sales. Similar conclusions have been reported in previous agricultural energy studies, where PV-dominant configurations were consistently favored for their cost-effectiveness and simplicity of integration [36–39]. Although the integration of wind turbines in the [G/PV/WT] and [G/PV/WT/B] systems enhanced emission reduction rates to 62.5% (Table 2), these configurations also required substantially higher capital investment, as illustrated in Figure 9. These findings resonate with earlier work in southern Ghana [42–44] and rural Malaysia [45–48], which similarly observed that while the inclusion of wind energy improves the renewable fraction of hybrid systems, the associated cost escalation often undermines economic competitiveness. Consequently, under current technology and price conditions, PV-dominated grid-connected systems remain more advantageous in regions such as Afyonkarahisar, where solar resources are relatively abundant (Figure 5a,b) and average wind speeds are modest (Figure 5d).

For off-grid configurations, the [Gen/PV/B] system offered the most balanced solution, combining a low NPC (USD 1.19M) and competitive LCOE (USD 0.342/kWh) with a 64.58% reduction in CO_2 emissions (Table 7). Seasonal generation patterns (Figures 14 and 15) demonstrate that PV supplies the bulk of energy in summer, while the diesel generator compensates for shortfalls in winter, thereby ensuring reliability. Comparable results were obtained by Woldegiyorgis et al. [100], Samatar et al. [101], and Eze et al. [102], who found that PV–diesel–battery hybrids provide the most practical compromise between cost and emissions in rural agricultural contexts. The cost breakdown (Table 8) further confirms that although the generator remains the dominant expense driver due to fuel consumption, PV integration substantially mitigates long-term operational costs. By contrast, fully renewable standalone systems ([PV/WT/B], [PV/B], [WT/B]) successfully achieved zero-emission targets but at prohibitive costs, with NPC values ranging between USD 2.54M and USD 4.52M (Table 7). This trade-off between environmental gains and financial feasibility is well documented in the literature. Ferreira et al. [26], Eze et al. [102], and Kumar et al. [103] similarly emphasized that while such systems are technologically feasible, their adoption hinges on significant reductions in battery and wind turbine costs. The present results reinforce this argument, indicating that zero-emission greenhouse operations are currently constrained more by economics than by technical feasibility.

The sensitivity analyses (Tables 5 and 9; Figures 12 and 16) underscore the vulnerability of hybrid energy investments to macroeconomic conditions. In grid-connected scenarios, payback periods ranged from 2.8 years under average assumptions to more than 25 years under high-inflation conditions (Figure 12). A similar sensitivity was observed in the off-grid [Gen/PV/B] system, where payback periods varied between 1.7 and 5.1 years depending on fuel price and solar irradiance (Table 10). Consistent with the conclusions of Kumar et al. [103] and the ESMAP report [32], the findings reaffirm that inflation and fuel price instability are pivotal factors affecting the financial performance of agricultural microgrids. Overall, this study confirms the conclusions of prior research that hybrid PV-based systems offer the most immediate benefits for agricultural applications, particularly when complemented by diesel backup in off-grid scenarios [100–103]. At the same time, it highlights the persisting gap between cost-optimal and environmentally optimal solutions: while PV–diesel–battery hybrids remain the most pragmatic choice today, the transition to fully renewable systems will depend on further cost reductions in storage and wind technologies. This aligns with global policy perspectives emphasizing that innovation in storage and cost-effective grid integration will be pivotal in enabling carbon-neutral agriculture [1,2,82].

5. Conclusions

In today's economic environment, where cost-efficiency is increasingly prioritized, the persistent rise in energy prices is compelling agricultural enterprises, much like other sectors, to seek alternative solutions to meet their energy demands and reduce expenditures. Hybrid energy systems that integrate solar and wind power with diesel generators as backup sources offer technically and economically sustainable options for meeting greenhouse energy requirements. The energy expectations of agricultural enterprises increasingly center around utilizing REN sources such as solar and wind, and ideally, selling excess energy back to the grid. This approach not only enables the generation of potential green electricity for peak demand periods but also contributes to reducing environmental pollutants and creating additional economic benefits.

A key contribution of this study lies in its systematic comparison of various hybrid system configurations, both grid-connected and off-grid, for high-demand facilities such as greenhouses. The scientific originality of this work lies in the fact that, unlike previous studies, which typically analyzed isolated system configurations, this research provides a comprehensive evaluation under consistent technical and economic assumptions. This broadens the understanding of optimal hybrid energy configurations, especially in agricultural settings, where operational reliability and economic feasibility are critical.

In a hybrid system, renewable sources are combined with fossil fuels for electricity generation. The primary objective of hybrid systems is to minimize fossil fuel consumption while maximizing cost-effective benefits for end-users. This study comprehensively analyzed the technical, economic, and environmental performance of both grid-connected and off-grid REN systems for greenhouse facilities. The most optimal hybrid system configurations were identified based on these evaluations. Considering the balance between cost-effectiveness, environmental impact, and operational reliability, the [G/PV] configuration was found to be the most viable option for grid-connected systems due to its low cost, reasonable emissions reduction, and ability to meet the energy needs of greenhouse operations. In off-grid systems, the [Gen/PV/B] configuration demonstrated similarly balanced performance, making it a suitable solution in terms of both cost efficiency and emissions mitigation.

This study also emphasizes the significant trade-off between environmental objectives and financial constraints. While the integration of batteries and wind turbines is appealing

for achieving carbon neutrality, the high costs associated with these technologies may limit their widespread adoption in economically constrained regions. On the other hand, generator-based systems, though cost-effective in some cases, are less desirable due to their high emissions and operational costs. This balance between economic feasibility and environmental impact is crucial in determining the viability of different configurations.

A major original aspect of this study is its inclusion of an extensive sensitivity analysis, exploring the impact of variables such as inflation, fuel price fluctuations, and changes in renewable energy resources on system performance. This is particularly relevant in today's context of economic uncertainty, providing a framework for understanding how external factors can significantly affect the viability of hybrid energy systems. Future research should focus on reducing the costs associated with battery storage and wind energy technologies to facilitate broader adoption of these sustainable energy solutions. Additionally, utilizing localized, high-resolution datasets will improve the accuracy of techno-economic analyses, as the specific meteorological and economic parameters of a region can greatly influence system performance and feasibility.

Moreover, there is a need for further investigation into emerging technologies, including advanced energy storage solutions such as hydrogen, and the integration of concepts such as agrivoltaics. These systems could further optimize energy use in agricultural settings. Detailed assessments of evolving energy sector policies, including incentive mechanisms and regulatory frameworks, should also be conducted to understand their impact on the financial viability and widespread adoption of hybrid energy systems. Through these efforts, future research can contribute to the development of robust and fully renewable energy solutions for the agricultural sector.

In conclusion, while this study presents several cost-effective and environmentally beneficial hybrid system configurations, it underscores the importance of addressing both economic and environmental factors to facilitate the adoption of renewable energy systems in agriculture. The findings contribute to a deeper understanding of the practical limitations of renewable energy integration, offering insights that are applicable to regions with similar economic and climatic conditions.

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