

RESEARCH ARTICLE

Hybrid PV/Wind/Grid Energy System for Commercial Bakeries: A Techno-Economic and Environmental Assessment

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Abstract: This study proposes a hybrid PV/wind/grid energy system for small urban bakeries and evaluates its technical performance, economic feasibility, and environmental impact within an integrated framework. Unlike previous studies that assess only economic or environmental aspects, this research combines both dimensions using HOMER Pro and PVsyst simulations over a 20-year project lifetime. The proposed system requires an initial investment of approximately \$10,350 and achieves a payback period of 2.28 years, demonstrating strong financial viability. After cost recovery, annual energy savings reach about \$4,380, along with an additional monthly income of nearly \$212 from surplus electricity under net-metering conditions, which further enhances its economic attractiveness. Environmentally, the system reduces CO₂ and other harmful emissions by up to 90% compared to conventional fossil-fuel-based bakery operations, significantly contributing to sustainability goals and cleaner urban environments. The novelty of this study lies in integrating HOMER Pro and PVsyst for simultaneous technical–economic–environmental optimization, applying the hybrid model to small-scale urban bakeries, and quantifying real emission reductions and financial returns under net-metering conditions, thereby providing a comprehensive and practical framework for future renewable energy applications in similar small-scale industries.

Keywords: renewable energy, hybrid energy system, conventional energy, economic impacts, environmental impacts

1. Introduction

In the modern world, energy demands are rising rapidly. Conventional fuels such as natural gas, coal, and wood not only deplete natural resources but also pose significant threats to the environment, climate, and human health. The global energy sector remains heavily reliant on fossil fuels, producing approximately 34 billion tons of CO₂ annually [1, 2]. To address these challenges, renewable energy sources such as solar, wind, and hydro are increasingly recognized as sustainable and environmentally friendly alternatives.

In Afghanistan, despite the considerable potential for solar and wind energy, the energy sector remains underdeveloped. Specifically, in a representative urban region of Afghanistan province, bakeries largely satisfy their energy needs through conventional fuels, which contribute to environmental pollution, high energy costs, and health issues. Currently, around 280 bakeries operate in the city [3], each consuming approximately 15kg of natural gas per day. Combustion of these fuels releases CO₂, SO₂, CO, NO_x, and PM_{2.5}, leading to elevated rates of respiratory diseases and contributing to climate change [4, 5].

In recent years, rapid advancements in solar energy technologies, particularly photovoltaic (PV) and hybrid photo-

voltaic/thermal (PV/T) systems, have significantly enhanced the efficiency and economic feasibility of renewable energy applications. Moreover, the integration of artificial intelligence (AI) techniques such as machine learning, neural networks, and optimization algorithms has enabled improved performance prediction, energy management, and system optimization in modern renewable energy systems. These intelligent approaches have demonstrated strong potential in enhancing energy efficiency, reducing operational costs, and ensuring system stability under varying environmental conditions. Therefore, combining hybrid renewable energy configurations with intelligent control strategies represents a forward-looking solution for addressing rising energy demand, environmental degradation, and sustainability challenges, particularly in developing regions [6].

The continuation of this scenario deteriorates urban air quality, endangers public health, and increases the dependency on energy imports. Therefore, hybrid renewable energy systems (PV/wind/grid) are considered a crucial alternative for enhancing energy sustainability, economic savings, and environmental protection. These systems, when deployed in place of conventional fuels, can reduce energy costs, improve air quality, and mitigate climate change impacts.

Recent advancements in solar energy include hybrid systems combining PV modules with thermoelectric generators (TEG), which utilize waste heat to increase overall efficiency. Techniques like phase change materials, nanofluids, and advanced

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cooling enhance system performance under high solar irradiance. Intelligent control strategies allow these systems to adapt dynamically to environmental conditions, making them effective for high-efficiency, multifunctional renewable energy applications, especially in regions with abundant solar potential [7].

The objective of this study is to assess the technical, economic, and environmental feasibility of implementing hybrid renewable energy systems for bakeries in a representative urban region of Afghanistan. Specifically, the study evaluates how these systems can reduce energy expenditures, minimize harmful emissions, and provide a sustainable approach to environmental protection. Moreover, the research examines the economic implications of hybrid system deployment, including potential challenges and opportunities, comparative benefits over conventional energy sources, and the positive effects on the local environment. Overall, this study provides a scientific foundation for the sustainable development of Afghanistan's energy sector and demonstrates that renewable energy can play a vital role not only in environmental preservation but also in economic growth.

2. Literature Review

In the context of the modern, rapidly developing world, the energy demand is increasing at an accelerating rate. Conventional fossil fuels such as natural gas, coal, and wood are contributing to the depletion of natural resources, environmental pollution, climate change, and serious threats to human health. The global energy sector remains largely dependent on fossil fuels, which generate approximately 34 billion tons of CO₂ annually [8, 9]. To address these challenges, renewable energy sources such as solar, wind, and hydropower have gained growing importance as sustainable and environmentally friendly alternatives [10].

Recent studies highlight that high-precision prediction of the remaining useful life (RUL) of lithium-ion batteries is crucial for safe and efficient operation, especially under complex working conditions with cell-to-cell variations and multi-factor coupling. Advanced data-driven approaches, such as deep learning, Long Short-Term Memory (LSTM), and adaptive correction strategies, enable robust RUL estimation by considering multiple state parameters (SOC, SOH, SOP) and external conditions. In particular, improved anti-noise adaptive LSTM models with feedback correction and multi-feature collaboration have shown significant improvements in prediction accuracy and robustness, providing a reliable foundation for battery management and energy system optimization [11].

Although recent studies have extensively applied AI techniques such as LSTM, Bayesian optimization, and adaptive learning models for battery state estimation and RUL prediction, the present research does not focus on battery modeling or AI-based control strategies. Instead, this study evaluates a battery-free grid-connected hybrid PV/wind/grid system from a techno-economic and environmental perspective. By eliminating battery storage, the system significantly reduces capital and replacement costs while relying on net-metering interaction with the grid to ensure reliability. Therefore, the contribution of this research lies in practical economic optimization and environmental impact assessment of a real commercial load, rather than algorithmic or AI-based system modeling.

Hybrid renewable energy systems (PV/wind/grid) have been proposed to improve energy reliability, economic efficiency, and environmental performance. International studies indicate that the limitations of fossil fuels and the challenges of climate change are the primary drivers of renewable energy development. According to the International Energy Agency, by 2050, nearly 70% of

global electricity will be supplied from renewable sources [12]. These sources not only reduce carbon emissions but also play a crucial role in ensuring economic stability, energy independence, and job creation [13].

TEG and concentrated photovoltaic thermal (CPV/T) technologies, which recover waste heat to simultaneously produce electricity and thermal energy. Techniques such as phase change materials, nanofluids, fins, reflectors, and advanced cooling strategies have significantly improved the efficiency and daily output of solar desalination and hybrid systems. These innovations, coupled with intelligent control strategies, enable high-efficiency, multifunctional renewable energy solutions, particularly in regions with high solar potential [14].

After discussing the global shift toward renewable energy and the benefits of hybrid PV/wind/grid systems, it is important to highlight the role of energy storage in enhancing system reliability and efficiency. Off-grid and grid-connected solar systems, coupled with batteries, super capacitors, and flywheel storage, ensure an uninterrupted electricity supply, maximize solar energy utilization, and reduce reliance on fossil fuels. Moreover, advanced hybrid energy storage systems integrate energy management strategies and optimized power converters, enabling efficient operation in real-world PV applications and offering insights for future deployment [15].

Recent studies have shown that accurate estimation of the state of charge (SOC) of lithium-ion batteries can be achieved using Bidirectional Long Short-Term Memory (BiLSTM) networks, where Bayesian Optimization is applied to select optimal model hyperparameters and the unscented Kalman filter reduces noise effects, providing a robust and reliable solution for battery management systems [16].

Unlike the advanced battery state estimation and RUL prediction studies based on LSTM and Bayesian optimization models [11, 16], which primarily focus on battery health monitoring and SOC estimation accuracy, the present study emphasizes techno-economic and environmental optimization of a grid-connected hybrid PV/wind system without battery storage. Therefore, instead of AI-based electrochemical modeling, this research integrates HOMER Pro and PVsyst to evaluate real-world commercial energy applications for small urban loads.

From an economic perspective, renewable energy systems contribute to long-term cost reduction, capital return, and the enhancement of local production. From an environmental standpoint, the reduction of carbon dioxide and other pollutant emissions helps purify the air and mitigate the impacts of climate change [17, 18]. In contrast, conventional energy sources such as diesel, coal, and petroleum cause air pollution, global warming, and health-related issues [18–20].

Global experience shows that hybrid renewable energy systems increase the stability of energy generation, offer economic benefits, and significantly reduce CO₂ emissions. For example, in countries such as Bangladesh and Indonesia, the implementation of hybrid systems in place of traditional diesel-based systems has reduced both costs and pollution levels [21, 22].

In Afghanistan, the development of renewable energy faces challenges related to investment, infrastructure, technical expertise, and security constraints [23, 24]. Nevertheless, the use of solar or hybrid systems for commercial units—such as bakeries—in the test system can provide a sustainable energy supply, reduce operational costs, and contribute to environmental protection.

Analytical findings indicate that the adoption of renewable energy plays a fundamental role in achieving energy sustainability, economic development, and environmental preservation. However, the lack of appropriate policies, financial resources, and

Table 1
Comparative analysis of hybrid renewable energy systems (HRES) from previous studies

No	System configuration	Optimization/software used	COE (\$/kWh)	NPC (\$)	CO ₂ emission (kg/year)	Main findings/notes
[25]	PV + Wind	HOMER	0.307	–	–	Small hybrid model; technical testing conducted in Bangladesh.
[26]	PV + WT + Battery (Off-grid)	HOMER Pro	0.137	45,000	68% Reduction vs Diesel	Economic and sustainable solution for rural electrification.
[27]	PV + DG + Batt	HOMER + RETScreen	0.156	61,200	30% Reduction	Hybrid system application for a healthcare center.
[28]	PV + Diesel + BESS	HOMER	0.264	72,300	↓ 32.9%	Power stability and CO ₂ reduction in Indonesian islands.
[29]	PV + WT + DG/PHES/BESS	HOMER Grid + MATLAB	0.03845	98,400	100% Renewable	Fully renewable system with high efficiency.
[30]	PV + WT + Grid (EV Charging)	HOMER + MATLAB	0.085	–	↓ 22%	Improved power efficiency for EV charging stations.
[31]	PV + WT + DG + Battery (Review)	Comparative Review	0.05–0.40	–	30–70% Reduction	Analytical study of global HRES projects.
[32]	PV + Wind + Biomass	HOMER	0.145	55,000	40% Reduction	Sustainable energy solution for rural areas.
[33]	PV + Solar Thermal + Battery	RETScreen	0.160	60,500	35% Reduction	Stability solution for small industrial units.
[34]	PV + WT + Diesel Generator	HOMER Pro	0.180	62,000	50% Reduction	HRES implementation for urban centers.

technical support limits the growth of this sector. Therefore, this study presents a scientific, technical, and economic model for the implementation of renewable energy systems for bakeries in the test system. A comparative analysis of hybrid renewable energy systems (HRES) from previous studies is presented in Table 1.

3. Research Methodology

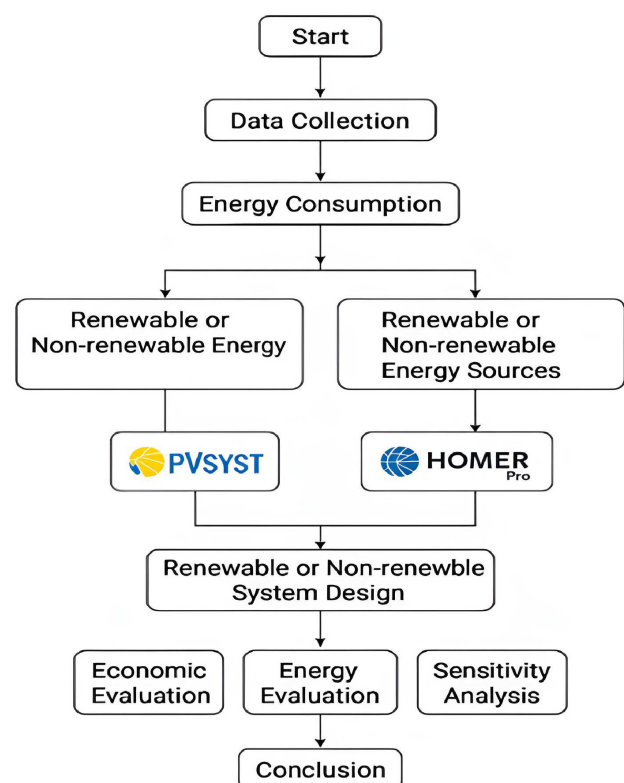
This study identifies the optimal hybrid energy systems for bakeries using HOMER Pro and PVSyst software. The analysis focuses on energy efficiency, economic feasibility, environmental impacts, and sensitivity assessment of various factors. The research employs a mixed-methods approach, combining descriptive and quantitative methods: the descriptive component examines the current state of energy use, while the quantitative component analyzes numerical data such as energy consumption, costs, and production capacities. The research methodology is illustrated in Figure 1.

The field assessment investigates the current status of conventional energy sources (wood, diesel, coal), their economic and environmental impacts, and subsequently evaluates the feasibility of solar energy implementation. Various configurations of hybrid systems are compared to propose economically and environmentally sustainable solutions.

3.1. Brief overview of the electricity distribution network in Ghazni Province

The electricity network in Ghazni Province is managed by the Da Afghanistan Breshna Sherkat (DABS) and is supplied

Figure 1
Research methodology flow chart



primarily through imported electricity. The network is connected to the national grid via 220 kV transmission lines, and the distribution capacity to the provincial center is approximately 12 MW, with a peak load of around 8 MW. When fully connected to all districts, the total consumption capacity reaches 100 MW [35, 36].

The region’s annual average solar radiation is 5.46 kWh/m²/day, according to NREL data, which is illustrated in Figure 2.

According to NREL data, the annual average wind speed in the studied province at a 30-m hub height reaches up to 13.97 m/s, with a mean speed of approximately 4 m/s. These data were used to assess the wind energy potential and are illustrated in Figure 3.

3.2. Statistical data of bakeries

For this study, 30 bakeries were selected from a total of 180 registered bakeries in the studied city to represent different areas of

Figure 2
Hourly solar radiation and temperature at a selected site during a year

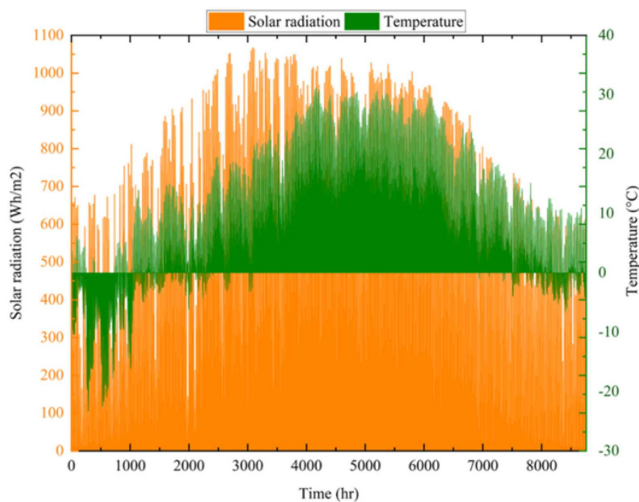
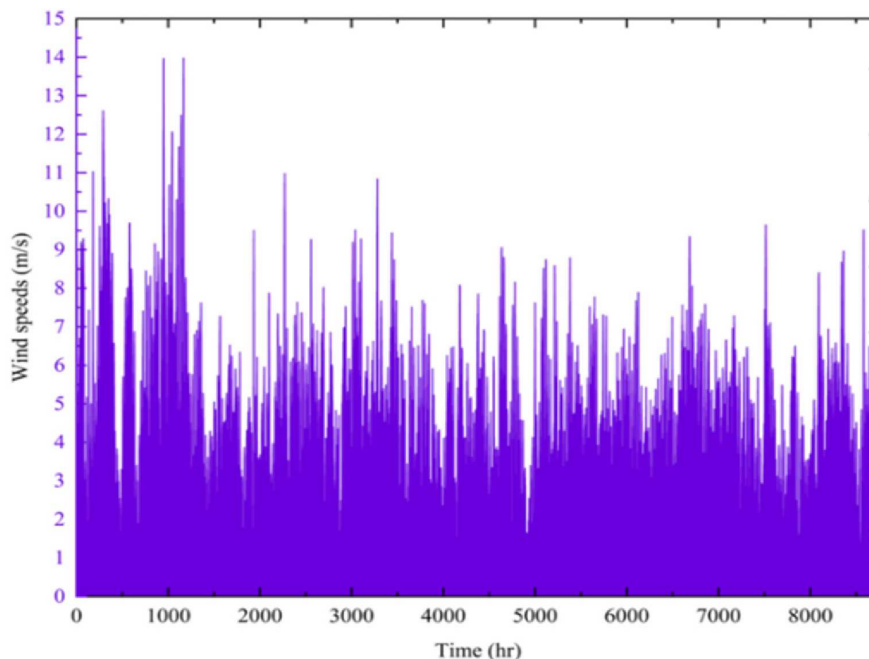


Figure 3
Hourly wind speed at 30 m height of a selected site during a year



the city. These units were chosen based on their operational scale (small, medium, large) and types of energy consumption (wood, coal, gas, electricity).

Survey results indicate that each bakery consumes approximately 15 kg of gas per day, produces around 600 loaves of bread, and the energy cost accounts for about 1.4% of the income per loaf. These data were utilized to evaluate the energy consumption and perform the economic analysis of the bakeries. The detailed energy consumption, production, and cost of a bakery (daily, monthly, and yearly), along with its size, are presented in Table 2.

3.2.1. Assessment of energy consumption for bakeries

For the efficiency of the hybrid system, it is essential to determine the precise energy consumption of the bakery. During the survey, the capacity and operating hours of all installed electrical appliances were recorded. Annual electricity consumption data for the bakery were collected to illustrate daily and seasonal energy consumption patterns.

The daily energy consumption of each appliance was calculated using the formula [37]:

$$E = P \times h \tag{1}$$

where E is the energy consumed, P is the appliance power rating, and h is the operating hours. All data were then compiled into the bakery’s load profile. The average daily electricity consumption for all equipment in a bakery was found to be 37.25 kWh, resulting in a monthly consumption of 1117.5 kWh.

HOMER software was used for computational evaluation, effectively capturing variations in consumption due to daily and seasonal changes. The detailed daily electricity consumption of all bakery equipment is summarized in Table 3.

3.3. Design of the hybrid energy system for the bakery

The objective of designing a hybrid energy system for the bakery is to ensure a sustainable energy supply, economic savings, and environmental protection. The system meets the bakery’s

Table 2
Energy consumption, production, and cost of a bakery (daily, monthly, yearly) along with its size

Item	Daily	Monthly (30 days)	Yearly (365 days)
Gas consumption (kg)	15	450	5,475
Gas cost (AFN)	780	23,400	284,700
Electricity cost (AFN)	50	1,500	18,250
Total energy cost (AFN)	830	42,900	302,950
Bread production per bakery (units)	600	18,000	219,000
Energy cost (% of income per loaf)	Approximately 1.4%	—	—

Note: All values are based on the average of the collected data for the respective items.

Table 3
Daily electricity consumption of all equipment in a bakery

Electrical equipment	Quantity	Power (W)	Operating hours (h/day)	Energy consumption (kWh/day)
CW-A5DI electrical oven	1	7000	5	35
LED groups	5	25	4	0.5
Water heater	1	1000	1	1
Exhaust fan	1	75	6	0.45
Television	1	100	3	0.3
Total daily energy consumption	—	—	—	37.25
Total monthly energy consumption (30 days)	—	—	—	1117.5

daily electricity demand using a combination of solar energy, wind energy, and the grid, thereby reducing the use of conventional fuels such as wood, coal, and natural gas.

The system design considers the bakery's daily energy consumption, solar and wind availability, and the efficiency of equipment, aiming to maintain continuous energy generation while managing costs effectively. System evaluation was carried out using PVsyst and HOMER software. PVsyst analyzes the annual solar system output, efficiency, and energy generation profile, whereas HOMER evaluates the economic, technical, and environmental aspects of the complete hybrid system. HOMER results identify the most economical and reliable configuration for the bakery and provide clear insights into initial costs, energy pricing, and CO₂ emissions.

3.3.1. Structure of the renewable energy hybrid system

Using HOMER software, multiple hybrid system configurations for the bakery were analyzed and compared to select the most economical and efficient system. The proposed system consists of:

- 1) 14 solar panels with a total capacity of 7 kW
- 2) 1 wind turbine rated at 2.5 kW
- 3) 1 hybrid inverter
- 4) Connection to the electricity grid

The electricity generated by the solar panels is transmitted through a direct current (DC) bus to the inverter, converted into alternating current (AC), and supplied to meet the bakery's daily electricity demand.

The system is connected to the grid via net metering, allowing it to draw energy from the grid during shortages and sell excess energy back to the grid. The overall structure of the proposed hybrid renewable energy system is illustrated in Figure 4. PVsyst software was used to analyze the solar system's capacity and

efficiency, while HOMER evaluated the economic, environmental, and energy performance aspects of the overall system.

3.3.2. Calculation of electricity consumption for the bakery

The total capacity of all electrical equipment in a bakery is 8.3 kW, with a daily energy consumption of 37.25 kWh (Table 4). This value serves as the basis for designing the bakery's hybrid system and for calculating the required solar and wind energy capacities.

3.3.3. Analysis of the load profile for the bakery

To accurately assess the bakery's energy requirements, hourly based load profiles were developed.

Daily Level: The highest consumption comes from the electric oven, operating in three shifts (morning, noon, and evening), with a total daily consumption of 37.25 kWh (Figure 5(a)).

Monthly Level: Energy consumption remains relatively constant throughout the year, with the peak occurring in July (Figure 5(b)).

Yearly Level: Equipment operating hours are fairly consistent, except during Ramadan, when morning and afternoon operating hours decrease (Figure 5(c)). These load profiles provide a critical basis for energy generation planning, inverter and battery sizing, and the effective design of the hybrid system.

3.3.4. Wind turbine model

The primary function of the wind turbine is to convert kinetic wind energy into electricity [31]. Using HOMER software, electricity production is calculated based on the turbine's hub height (30 m), wind speed, and power curve, while adjusting for actual air density conditions [37]. In this study, the Xzeres Skystream 3.7 turbine (maximum output 2.4 kW) was used. The total initial cost

Figure 4
Structure of the renewable energy hybrid system

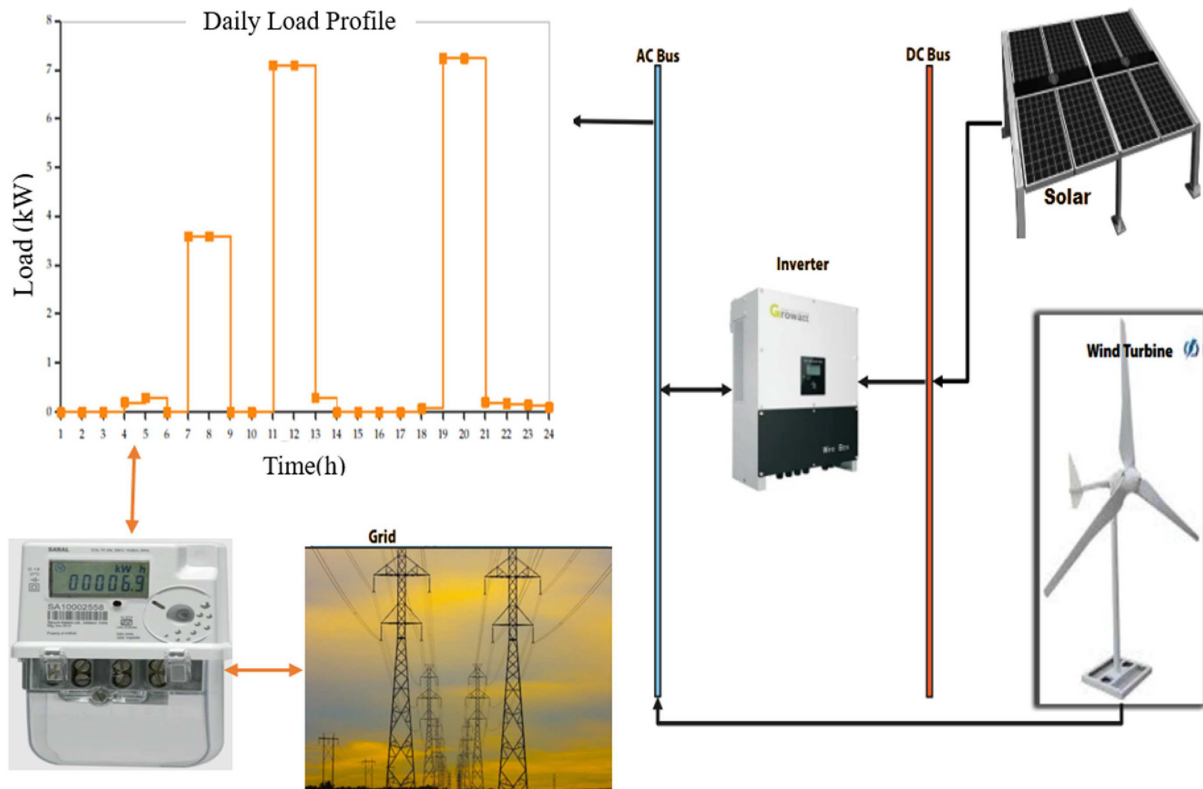


Table 4
Electricity consumption for a bakery

Daily energy consumption of all electrical equipment (kWh/day)	Total capacity of all electrical equipment in a bakery (kW)
37.25	8.3

is \$ 8357, and it is profitable over a 20-year lifetime. Additional technical specifications are provided in Table 5. <https://www.mwps.world> > ... > (SKYSTREAM 3.7-2.4kW Wind Turbine Sale)

$$P_{WGT} = \left(\frac{\rho}{\rho_0}\right) P_{WGT, STC} \tag{2}$$

In Equation (2) [38, 39], P_{WGT} represents the power output of the wind turbine (in kW), and $P_{WT, STP}$ is the power produced by the turbine under standard temperature and pressure conditions. Here, ρ is the actual air density (kg/m^3), and ρ_0 is the air density under standard conditions, with a value of 1.225 kg/m^3 .

HOMER software calculates the wind speed at the turbine hub height for each time step. This calculation is based on the data provided in the wind resource file and wind shear effects.

- 1) If the logarithmic law is selected, HOMER computes wind speed using a specific logarithmic equation (Equation (3)) [37].
- 2) If the power law is used, the calculation is performed using a different power-law equation (Equation (4)) [37].

Based on these equations, the wind power curve is generated, as illustrated in Figure 6 (HOMER).

$$U_{hub} = U_{anem} \times \left(\frac{Z_{hub}}{Z_0}\right) \left(\frac{Z_{anem}}{Z_0}\right) \tag{3}$$

$$U_{hub} = U_{anem} \times \left(\frac{Z_{hub}}{Z_{anem}}\right)^\alpha \tag{4}$$

In the above equations:

- U_{hub} is the wind speed at the turbine hub height (m/s).
- U_{anem} is the wind speed measured at the anemometer height (m/s).
- Z_{hub} is the height of the turbine hub (m).
- Z_{anem} is the height of the anemometer (m).
- Z_0 represents the surface roughness length (m), indicating the terrain's surface irregularity.

α is a constant in the power law, representing the rate or intensity of wind speed change with height.

The selected Xzeres Skystream 3.7 [2.4 kW] wind turbine was evaluated using HOMER software. The turbine is installed at a hub height of 30 m, where the average wind speed is approximately 5.3 m/s. At this wind speed, the turbine generates 0.64 kW of nominal power, contributing 30.5% of its rated capacity and 41.2% of the total system output.

The turbine's daily energy production over 24 h is illustrated in Figure 7, showing maximum production in March and minimum production in August. All related economic and energy data are presented in Table 6.

Figure 5
Load profile of the bakery—(a) daily, (b) monthly, and (c) yearly (kW)

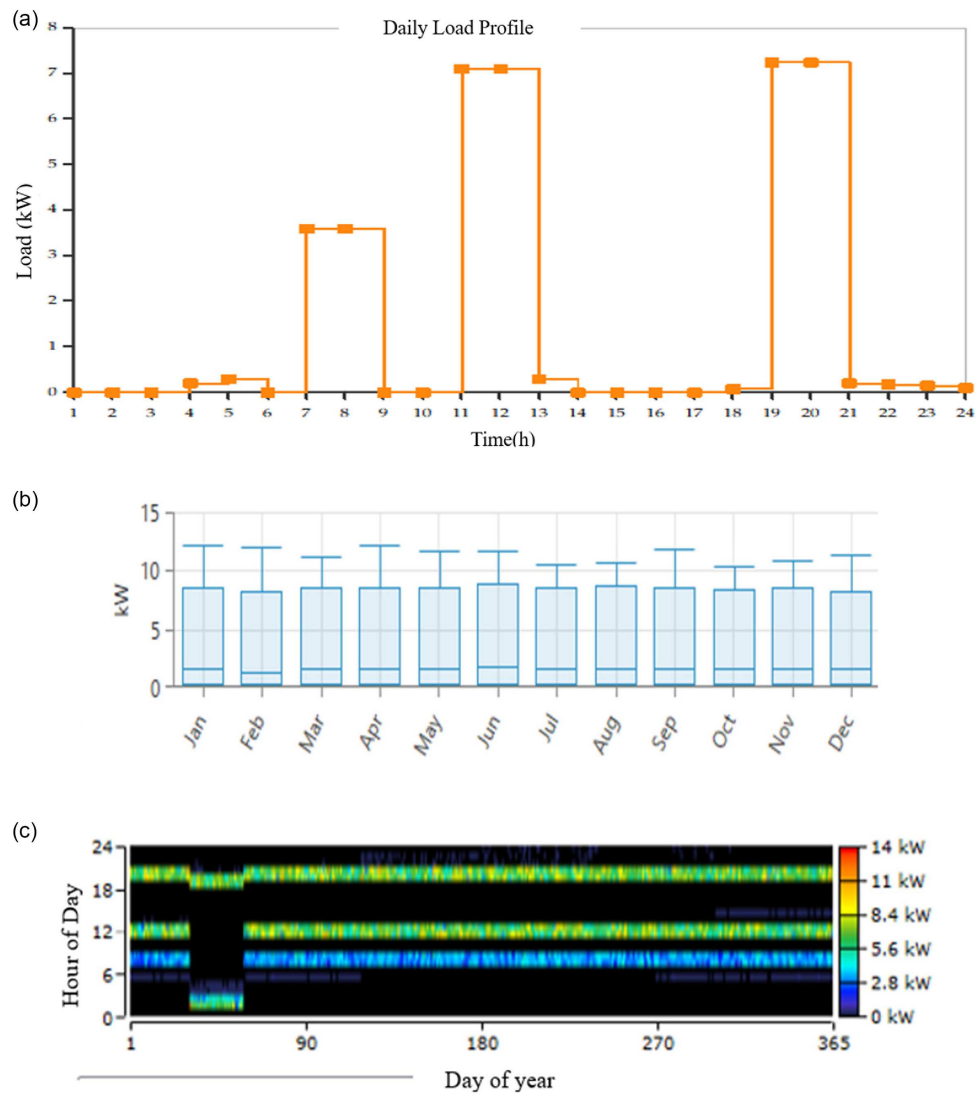


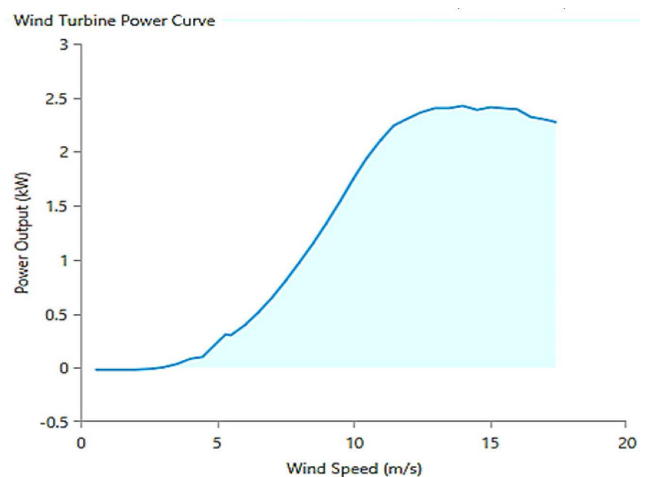
Table 5
Technical specifications of the wind turbine (MWPS, 2025)

Parameter	Specification
Turbine model	Xzeres Skystream 3.7 [2.4 kW]
Maximum output	2.4 kW (at 13 m/s wind speed)
Rotor diameter	3.72 m
Weight	77 kg

3.3.5. Solar panels (PV model)

The selection of solar panels for the bakery’s renewable hybrid energy system was carried out using PVsyst and HOMER Pro software. PVsyst was used to evaluate the energy production and efficiency of the solar panels, while HOMER assessed the economic feasibility and overall energy output. Based on solar irradiance and geographical data for Ghazni Province, the TSM-500-NEG18R-28-20 Vertex solar panel model was selected, with each panel rated at 500 W. A total of 14 solar panels were used for the system. According to PVsyst, the tilt angle of the panels was set at 33°, and the total area of all panels is

Figure 6
Power curve of the wind turbine (HOMER)



approximately 31.1 m². All technical specifications are provided in Table 7.

Figure 7
Power output of the wind turbine

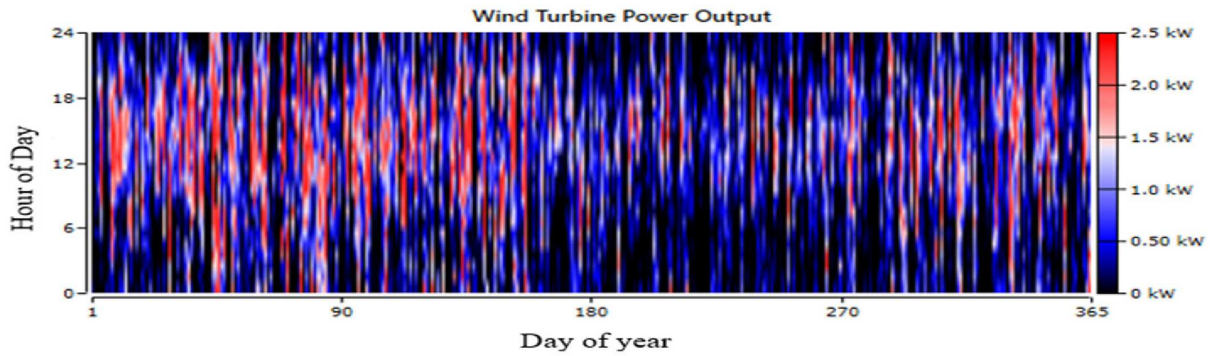


Table 6
Energy and economic data of the wind turbine

No.	Parameter	Value	Unit
1	Total capacity of wind turbine	2.10	kW
2	Nominal power output	0.640	kW
3	Capacity factor	30.5	%
4	Total energy production	5604	kWh/year
5	Minimum power output	0	kW
6	Maximum power output	2.42	kW
7	Wind energy penetration	41.2	%
8	Operating hours	7388	h/year
9	Average cost of energy	0.0993	\$/kWh

Table 7
Technical specifications of TSM-500-NEG18R-28-20 vertex solar panels (PVsyst)

Parameter	Value	Unit
Model name	Trina solar	-
Type	Monocrystalline	-
	500 W	
Maximum power (Pmax)	500 ± 5%	W
Voltage at maximum power (Vmpp)	33.30	V
Current at maximum power (Impp)	15.03	A
Open-circuit voltage (Voc)	40.10	V
Short-circuit current (Isc)	15.86	A
Operating temperature range	-40 to +60	°C
Weight	23.5	kg
Length	1961	mm
Width	1134	mm
Area	2.064	m ²

In the system, the selected solar panels generate approximately 12,229 kWh of energy annually, covering a daily consumption of 33.5 kWh, while the excess energy is exported to the grid. The performance ratio (PR) of the solar panels is 89.5%, calculated for all months of the year using the PVsyst software. The PR indicates the efficiency level of the solar system's actual output compared

to its theoretical production. The monthly variation of the solar system PR is illustrated in Figure 8.

In the renewable hybrid energy system, solar panels contribute 47.7% of the total generated energy. According to the evaluation conducted using HOMER software, all solar panels operate for approximately 4387 h per year, as illustrated in Figure 9, showing

Figure 8
Solar system performance ratio (PR) graph (PVsyst) Figure_08

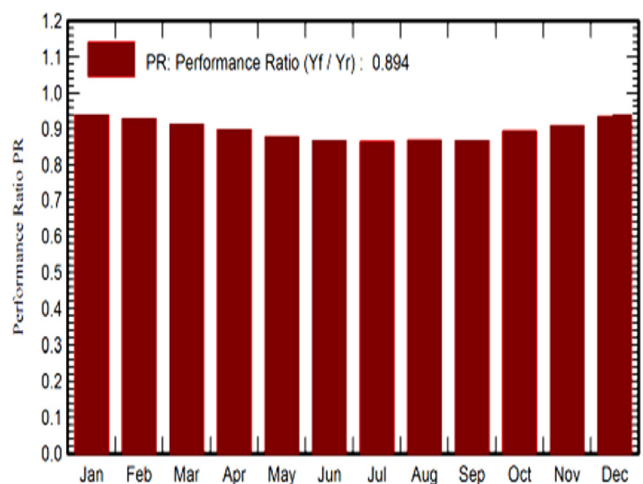


Figure 9
Annual nominal energy production of solar panels (PVsyst)

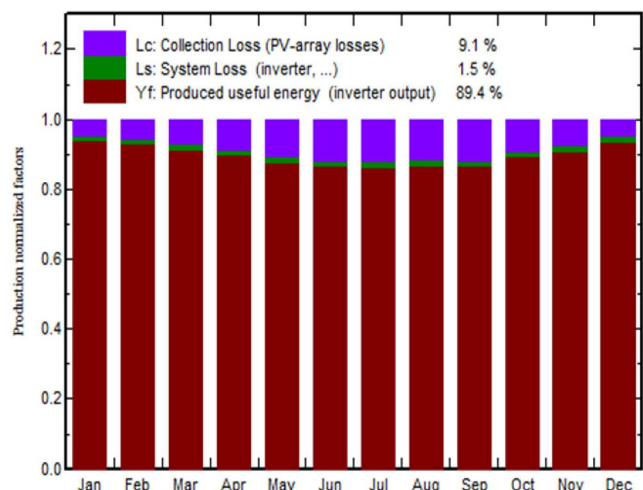
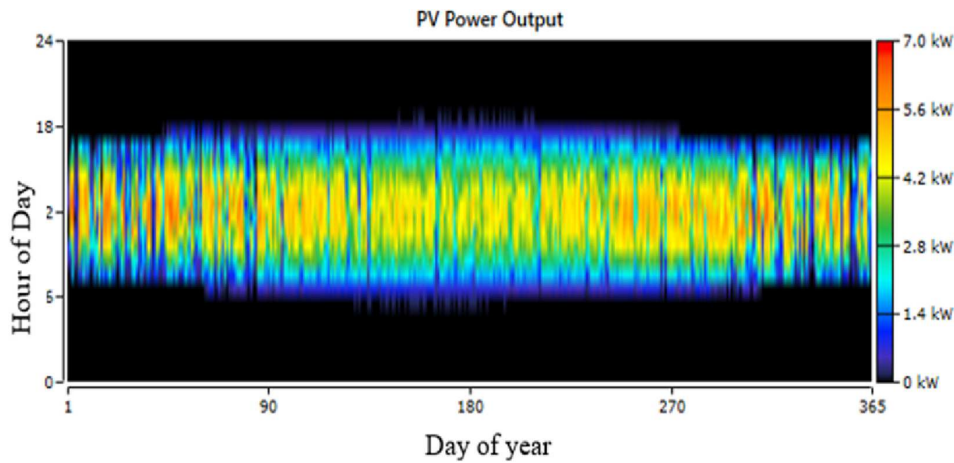


Figure 10
Solar panel power output spectrum (HOMER)



the hourly energy generation profile. Typically, the panels produce electricity from 7:00 AM to 5:00 PM, with varying intensity throughout the day.

In Figure 10, the monthly solar energy production is presented, displaying both the energy output and loss percentages. Based on PVsyst data, the collection loss ($L_c = 0.55 \text{ kWh/kWp/day}$) indicates that about 9.1% of the total generated energy is lost due to technical limitations, dust accumulation, shading, or high temperature—collectively referred to as array losses. The system losses ($L_s = 0.09 \text{ kWh/kWp/day}$) represent around 1.5% energy loss occurring in other components such as the inverter, cables, or power conversion process.

The remaining portion, Y_f (useful produced energy) = 89.4%, represents the net usable energy effectively delivered to the consumer. This analysis demonstrates that the selected 7 kW solar system achieves approximately 89.4% net energy efficiency, with minimal energy losses, indicating excellent operational performance

3.3.6. Inverter model

The primary function of the inverter is to convert the DC electricity generated by the solar panels into AC efficiently, so that it complies with grid standards. The inverter’s output power is calculated using the following equation [39–41]:

$$P_{OUT} = P_{IN} \times \eta_{inverter} \quad (5)$$

In this equation, $\eta_{inverter}$ represents the efficiency of the inverter, P_{IN} is the input power, and P_{OUT} is the output power. In this study, a Growatt MOD 13KTL3-X. An OND inverter is used, which has an efficiency of 95%, a lifespan of 20 years, and an initial cost of \$1400. The replacement cost is estimated at 90% of the initial cost, and the annual operation and maintenance cost is \$10, ensuring the reliable performance of the overall system. The detailed technical specifications of the inverter are presented in Table 8.

The inverter operates for approximately 4387 h per year. During this period, it produces 11,617 kWh of useful AC electricity from a total DC input energy of 12,229 kWh, meaning that about 611 kWh is lost in the DC-to-AC conversion within the inverter (HOMER).

Table 8

Technical specifications of the selected inverter (PVsyst)

Name	Growatt
Model	MOD 13KTL3-X
Unit nominal power	13.0 kWac
Operating voltage	140–1000 V
Maximum PV power	19.5 kw
Nominal MPP voltage	580 V
Maximum current per MPPT	26 A
Frequency	50–60 HZ
Efficiency	95%
Lifetime	20 years

3.3.7. Connection to the network (grid model)

In the hybrid energy system, the grid connection enables bi-directional interaction: if the system’s generation meets the load demand, the excess energy is fed into the grid, and if the generation is insufficient, the grid supplies the remaining demand. This interaction ensures continuous energy availability, reliable system operation, and effective coordination between the renewable energy sources and the grid (Equation (6)).

$$\text{Net Power Balance} = P_{gen} - P_{load} \quad (6)$$

In the hybrid system, P_{gen} represents the generated energy, and P_{load} represents the load demand. If generation exceeds demand, the excess energy is exported to the grid, and if generation is insufficient, the system draws energy from the grid. The DABS electricity price is \$0.22 per kWh for consumption, while the grid purchases excess energy at \$0.08 per kWh. The bakery’s energy demand is highest during morning and evening hours, which cannot be fully met by solar panels and wind turbines alone. Therefore, the system is grid-connected: energy is drawn from the grid when needed, and excess energy is sold back to the grid. Over one year, the system draws 7787 kWh from the grid and sells 11,412 kWh. The net energy exported to the grid is therefore 3625 kWh, generating a revenue of \$212 from energy sales (Table 9).

In the table, the negative sign (–) in the “Net energy exchanged” column indicates that, at a given time, the amount of

Table 9
Grid energy imported and exported (HOMER)

Month	Energy imported (kWh)	Energy exported (kWh)	Net energy exchanged (kWh)	Peak load (kW)	Energy cost (\$)
March	654	1,091	-437	10	0
April	548	1,055	-507	12	0
May	588	1,065	-477	12	0
June	657	905	-248	11	0
July	696	860	-164	11	0
August	708	827	-119	11	0
September	648	876	-228	11	0
October	584	956	-372	10	0
November	634	839	-205	11	0
December	706	794	-88	11	0
January	702	862	-161	12	0
February	663	1,282	-618	12	0
Annual total	7,787	11,412	-3,625	12	212

energy sold to the grid exceeds the energy purchased. If the negative sign is absent, the energy purchased from the grid is greater than the energy exported. The higher energy sold in the month of February (Hut) is due to the increased bakery consumption during Ramadan, when daily consumption is higher compared to other months, but lower during specific hours of the day. The energy purchased from the grid is illustrated in Figure 11, evaluated over all 365 days of the year and 24 hours per day. Analysis shows that most energy is drawn from the grid between 7:00 PM and 9:00 PM, whereas no energy is drawn from the grid between 1:00 PM and 6:00 PM. Figure 12 shows the amount of energy generated by the wind turbine and solar panels that is sold to the

grid. The profile indicates that most energy is exported when the bakery load is low, typically between 9:00 AM and 11:00 AM in the morning and between 1:00 PM and 4:00 PM in the afternoon, when a large portion of the generated energy is fed into the grid.

4. Results and Discussion

4.1. Energy assessment

The selected optimal and reliable hybrid system for the bakery, comprising solar panels (PV), a wind turbine (WT), and a grid connection (grid), meets the entire energy demand of

Figure 11
Profile of energy purchased from the grid

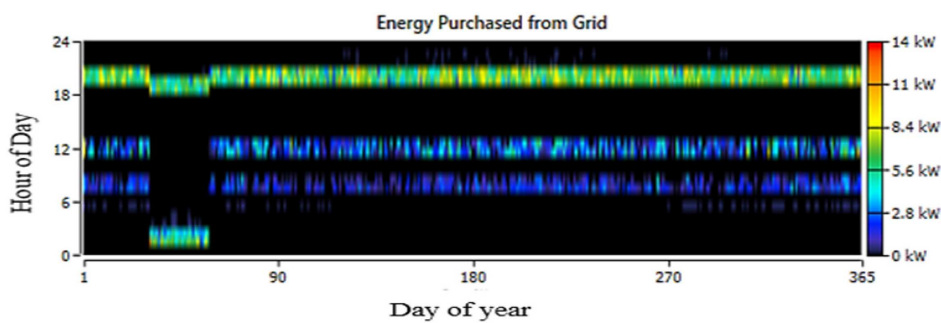
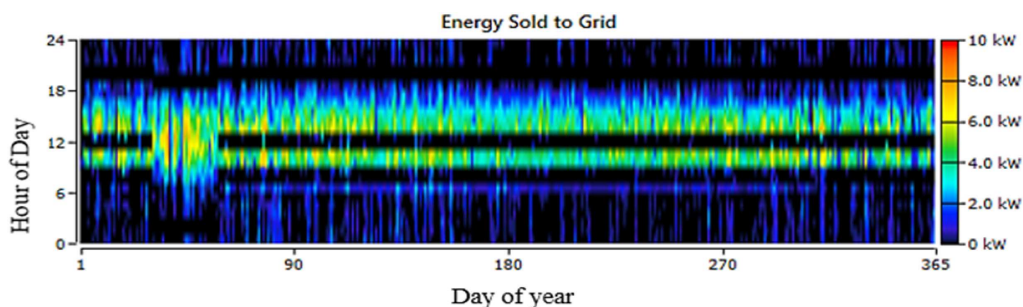


Figure 12
Profile of energy sold to the grid



the bakery. The technical configuration and components of this system are presented in Table 10, as determined using HOMER software.

Table 10
Selected hybrid system configuration for the bakery

No	Component	Name	Size	Unit
1	PV	TS-Si-mon	7	KW
2	Wind turbine	Xserve's Skystream 3.7 [2.4kW]	1	
3	Inverter	Growatt	13	KW
4	Grid	Grid	13	KW

The energy assessment for the bakery was carried out using PVsyst and HOMER software; HOMER evaluated the technical and economic performance of the entire hybrid system, while PVsyst analyzed the solar panel production and its interaction with the grid. Calculation results, including energy generation, consumption, purchased energy, and energy sold to the grid, are summarized in Table 11.

Table 11
Energy production and consumption in the system

Energy source/flow	Energy (kWh/year)	Share (%)
Solar PV generation	12,229	47.7
Wind turbine generation	5,604	21.9
Energy purchased from grid	7,787	30.4
Total generated energy	25,620	100
Total consumed energy	13,908	55.6
Energy sold to grid	11,412	44.4
Total energy flow	25,320	100

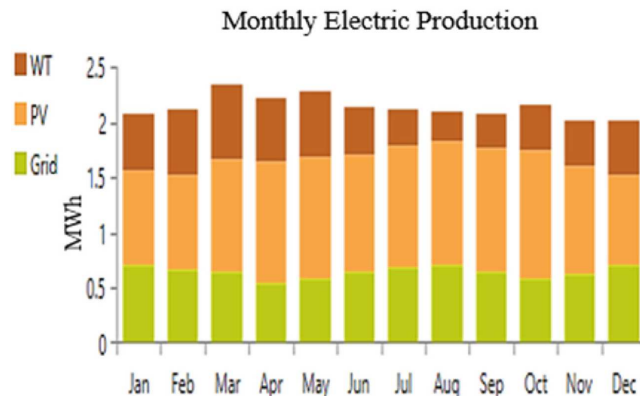
4.2. Energy assessment using HOMER Pro software

HOMER Pro software was used to evaluate the hybrid energy system for the bakery, including solar panels, a wind turbine, and a grid connection. The objective was to meet the bakery's daily electricity consumption of approximately 38 kWh. The software. The HOMER software results indicate that the annual energy generation for the bakery is approximately 25,620 kWh. About 70% of this energy is produced from renewable sources, while the remaining 30% is supplied from the grid, which is sufficient to meet the bakery's daily electricity requirements. It should be noted that specific solar panels were not selected in HOMER, so solar losses are not displayed; only minor losses occur at the inverter stage. The selected wind turbine has zero losses, and no additional storage or backup is considered in the system. The monthly energy generation profile is shown in Figure 13.

4.3. Energy assessment based on PVsyst software

The solar energy assessment for the bakery was conducted using the PVsyst software, which is utilized for accurate energy prediction, performance evaluation, and analysis of the

Figure 13
Monthly energy generation (HOMER)



generation potential of the solar system. For the test system, the annual horizontal irradiation is 1,917.9 kWh/m², with the highest levels occurring in May and June. The diffuse irradiation is 520.9 kWh/m², accounting for approximately 27% of the total irradiation, indicating the clarity of the local climate. The average temperature of 9.96 °C is suitable for optimal solar panel performance, and the tilt and orientation of the panels have been optimized, resulting in an effective irradiation of 2,164.3 kWh/m².

The annual energy production of the solar panels is 12,229 kWh, of which 5,409 kWh meet the bakery's demand, 8,417 kWh is fed into the grid, and 8,269 kWh is drawn from the grid to compensate for deficits. HOMER Pro results indicate that 7,787 kWh is drawn from the grid, covering approximately 30% of the user's needs. The PVsyst software's probabilistic annual production estimates are P50 = 13,826 kWh, P90 = 13,280 kWh, and P95 = 13,126 kWh, reflecting the reliability of the system and its resilience against climatic variations. The annual production variability is calculated as 426 kWh, indicating the possible range of system output fluctuations.

The curve shown in Figure 14 represents the probability distribution of the solar system's annual energy production. This curve follows a normal (Gaussian) distribution, peaking at the P50 point, which indicates the most probable energy output. Production values around P50 are therefore the most likely, whereas lower or higher outputs occur with decreasing probability. A detailed summary of the monthly energy balance, including key results and system performance indicators, is provided in Table 12.

4.4. System losses

Figure 15 shows the different stages of energy transfer from solar irradiation to the grid and the losses at each stage. The annual horizontal irradiation is 1918 kWh/m², which increases by 15.2% on the tilted panel surface, reaching 2164 kWh/m². About 2.1% loss occurs due to the angle of incidence (Incidence Angle Modifier (IAM)). Based on the solar panels' Standard Test Conditions, the system efficiency is 22.5%, and the total estimated energy production is 15,164 kWh. Due to temperature effects, irradiation variations, and panel mismatch, approximately 8.2% losses occur. Additionally, 3% more losses arise from cable resistance and inverter conversion. As a result, the usable energy at the inverter output is 13,825 kWh, of which 5,409 kWh is directly consumed by the user, 8,417 kWh is exported to the grid, and 8,269 kWh is drawn from the grid to compensate for energy

Figure 14
Probability distribution graph

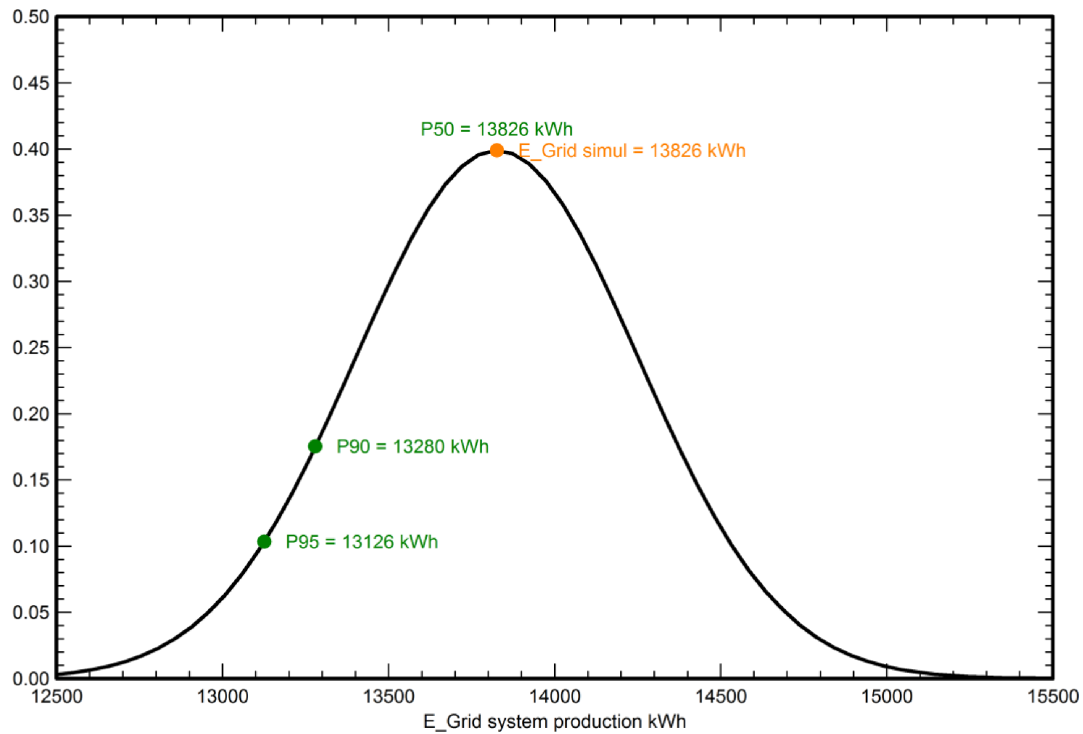


Table 12
Monthly energy balance (balances and main results)

Month	GlobHor (kWh/m ²)	DiffHor (kWh/m ²)	T_Amb (°C)	GlobInc (kWh/m ²)	GlobEff (kWh/m ²)	EArray (kWh)	E_User (kWh)	E_Solar (kWh)	E_Grid (kWh)	EfGrd (W9h)
January	93.3	27.9	-2.12	151.5	149.5	1012	1162	374	374	550
February	105.6	33.04	-0.41	147.3	149.9	973	1049	362	362	595
March	144.2	48.67	4.26	173.4	170.3	1127	1162	428	679	673
April	177.3	55.5	9.96	185.8	181.3	1188	1124	452	717	734
May	226.6	57.35	14.91	211.7	206.1	1324	1162	508	794	691
June	232.5	56.4	19.57	205.7	199.9	1270	1124	489	759	635
July	213.9	65.1	21.55	195.2	185.2	1299	1203	471	721	665
August	197.5	57.6	20.28	197	192.2	1218	1162	463	734	698
September	171.3	43.8	16.01	197.2	193	1218	1164	463	734	661
October	153.1	29.14	9.84	210.9	207.5	1342	1162	529	791	632
November	113.7	22.2	4.74	187.1	179.4	1176	1047	475	650	650
December	89	24.18	0.27	152.7	154	1013	1162	404	591	757
Year	1917.9	520.94	9.96	2209.6	2164.3	10465	13678	5409	8417	8269

deficits. This analysis demonstrates that minimizing losses in the solar system is critical for maximizing system performance, economic efficiency, and sustainability. Reduced losses not only increase energy utilization but also extend the system’s lifetime and ensure better returns for investors.

4.5. Economic assessment of the designed system for the bakery

The optimal configuration of the hybrid energy system for the bakery was obtained by minimizing the overall system cost, primarily through the reduction of the levelized cost of

energy (LCOE) and the net present cost (NPC). These economic indicators were evaluated using HOMER software, incorporating the capital recovery factor in the NPC formulation. The analysis was conducted under realistic financial assumptions, including a discount rate of 8% and an escalation rate of 2%. The technical characteristics of the proposed system are presented in Table 13, while the detailed energy production and distribution are illustrated in Table 14, and the corresponding economic evaluation is provided in Table 15.

The relatively low LCOE obtained in this study (0.0213 \$/kWh) can be attributed to several key factors. First, the proposed hybrid system does not include battery storage, which

Figure 15
System losses diagram (PVsyst)

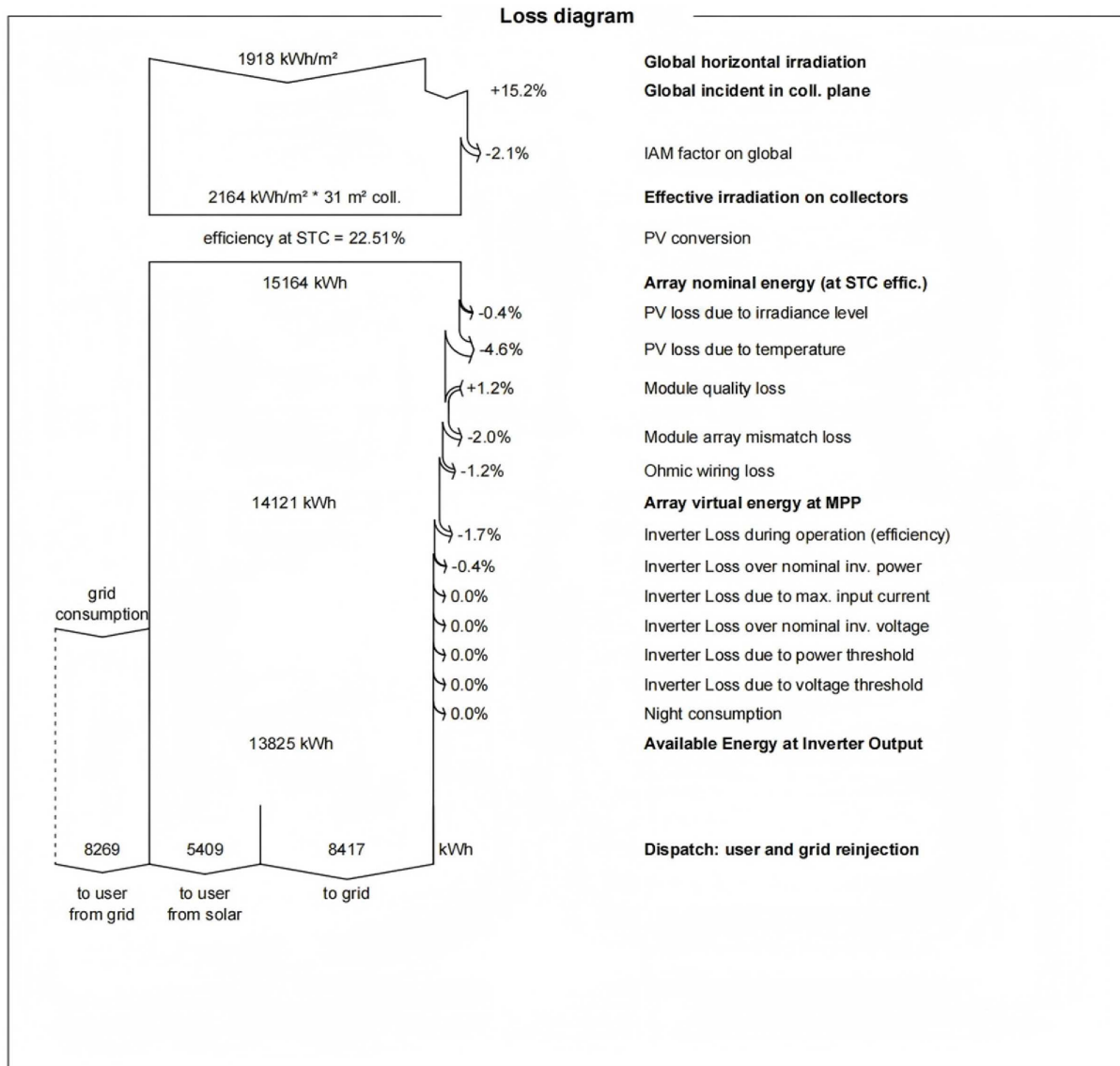


Table 13
Technical specifications of the hybrid system

No.	Equipment	Specifications
1	Solar panels	14 × TSM-500-NEG18R-28-20, total capacity 7 kW, total area 29 m ²
2	Wind turbine	Xzeres Skystream 3.7, capacity 2.4 kW, installation height 35 m, annual production 5,604 kWh, initial cost \$6,000
3	Inverter	Growatt MOD-13KTL3-X.OND, efficiency 95%, lifetime 20 years, initial cost \$1,400, annual maintenance \$10

Table 14
Energy production and distribution

Indicator	Value
Annual energy production	25,620 kWh
Solar panels contribution	47.7% (12,229 kWh)
Wind turbine contribution	21.9% (5,604 kWh)
Grid energy	30.9% (7,787 kWh)
Consumed energy	55.6%
Lost or sold energy	44.4%

significantly reduces capital and replacement costs. Second, the system benefits from grid connection through a net-metering mechanism, allowing excess renewable energy to be exported

and reducing the effective cost of electricity. Third, local labor and installation costs in Afghanistan are considerably lower compared to international benchmarks, further decreasing the overall system cost. In addition, the high solar irradiation and favorable wind conditions in the investigated distribution network enhance system productivity, leading to lower energy costs over the project lifetime. Using the hybrid system, the bakery

Table 15
Economic assessment

Indicator	Value
Net present cost (NPC)	\$ 83357
Levelized cost of energy (LCOE)	\$0.0213 /kWh
Annual net revenue	\$215–\$313
Payback period	2.28 years
Internal rate of return (IRR)	9.8%

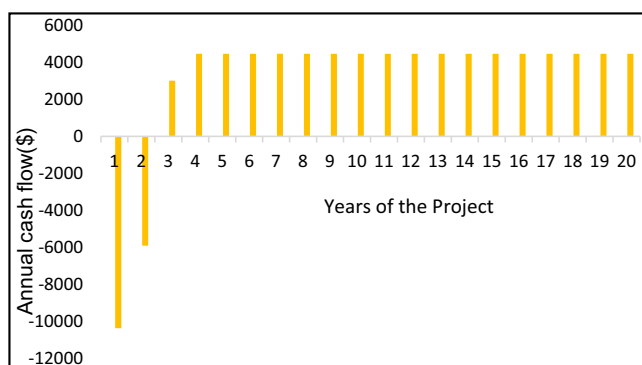
no longer requires conventional fuels such as gas; energy costs are reduced by nearly 50%, and CO₂ emissions are lowered to zero. This system provides a long-term, economical, clean, and sustainable energy solution. The initial cost of the new system for a bakery is presented in Table 16.

Table 16
Initial cost of the new system for a bakery (\$)

Equipment	Quantity	Unit price (\$)	Total initial cost (\$)
Hybrid renewable energy system	1	8,500	8,500
CW-A5DI electrical oven	1	1,200	1,200
FKJ-B 2KW 48V controller	1	350	350
Cables	1	100	100
Installation of some equipment	1	200	200
Total cost			10,350

The proposed hybrid energy system (PV/WT/grid) for the bakery includes the CW-A5DI electric oven, wind turbine, controller, cables, and installation costs, with a total initial cost of approximately \$10,350. For comparison, the current conventional system (using natural gas and electricity) has a daily cost of about 830 AFN (≈ \$12), a monthly cost of around \$360, and an annual cost of approximately \$4,380. The cash flow analysis of the proposed hybrid system is illustrated in Figure 16.

Figure 16
Cash flow diagram of the new system for the bakery



Economic analysis shows that the initial cost of the new system can be recovered in about 2.28 years through savings from daily energy expenses. After this period, the bakery will save on energy costs for about 17.72 years. Additionally, the system allows for approximately \$212 of extra monthly income through energy sold to the grid. Considering the annual maintenance cost of equipment (\$82), the total annual financial benefit is roughly \$4,530. This analysis indicates that the proposed hybrid system not only reduces energy costs but also ensures economic profitability and long-term financial stability for the bakery.

$$\text{Payback Period} = \frac{\text{Initial Investment}}{\text{Gas saving per year} + \text{Grid sell profit per year}} \quad (7)$$

Initial Investment: The estimated cost for one bakery is \$10,350. Gas Saving per Year: The amount of money saved annually by reducing gas consumption, considering the daily cost per bakery is approximately \$12. Grid Sell Profit per Year: The profit earned by selling excess energy generated from solar panels and wind turbines to the grid, calculated for one year, excluding equipment operation and maintenance costs, is \$212. Payback Period: The time required for the new system to recover the invested capital. The economic comparison of conventional and hybrid systems is presented in Table 17.

$$\text{Payback Period} = \frac{10350 \$}{12 \times 360 \$ + 212 \$} \approx 2.28 \text{ year} \quad (8)$$

4.6. Environmental assessment of the new hybrid energy system for the bakery

In the studied city, the daily consumption of 15 kg of natural gas by 280 bakeries releases harmful gases that have serious impacts on both the environment and human health. The annual energy consumption of bakeries from conventional fuels results in emissions of CO₂, CO, NO, SO₂, and PM_{2.5}. The detailed annual air pollution emissions from conventional fuel use in bakeries are presented in Table 18.

Bakeries in the test system primarily rely on natural gas and electricity, which results in high economic costs and environmental issues. The proposed new hybrid energy system (PV + Wind + Grid) makes energy consumption more economical, balanced, and sustainable. The total initial cost of the system is approximately \$10,350, with a payback period of 2.28 years. Technical assessment shows that the combination of solar panels, wind turbines, and grid balances energy production, while environmental assessment indicates that CO₂ emissions are reduced by up to 90%. Consequently, this system provides bakeries with a long-term, economical, clean, and sustainable energy solution. A comparative analysis of traditional and hybrid (PV–wind–grid) energy systems in terms of economic, technical, and environmental aspects is presented in Table 19. Furthermore, the optimization models and key economic indicators of the PV–wind–grid hybrid system are summarized in Table 20.

Compared to previous hybrid systems reported in Ma et al. [42] and Hai et al. [46], the proposed system achieves one of the lowest LCOE values (0.0213 \$/kWh), mainly due to grid integration without battery storage and high solar irradiation levels.

Table 17
Economic comparison of conventional and hybrid systems

Indicator	Conventional system (gas/wood)	Hybrid system (PV/wind/grid)	Description
Initial cost	\$3,000	\$10,350	A hybrid system has a higher initial investment
O&M cost	High	Very Low	Solar and wind systems require minimal maintenance
COE	\$0.22/kWh	\$0.099/kWh	Nearly 55% reduction in unit energy cost
NPC	–	–	According to HOMER calculations, the value is relatively low
Payback period	–	2.28 years	Indicates economic feasibility
Annual saving	–	\$4,380	Savings in fuel and electricity costs
Grid sell income	\$0	\$212	From the net-metering system

Table 18
Annual air pollution emissions from conventional fuel use in bakeries

Gas/particle	Per day per bakery	Annual total for all bakeries in the city (t)
CO ₂	41.25 kg	4,215
CO	75–150 g	7.67–15.33
NO	15–30 g	1.53–3.07
SO ₂	0.015 kg	≈ 4.4
PM2.5	0.015 kg	≈ 4.4

Table 19
Comparative analysis of traditional and hybrid (PV–wind–grid) energy systems in economic, technical, and environmental aspects

Indicator	Conventional system (Gas + Electricity)	New hybrid system (PV + Wind + Grid)
Initial cost	–	\$10,350
Daily energy cost	\$12 (~830 AFG)	\$0
Annual energy cost	\$4,380	–
Payback period	–	2.28 years
Annual energy production	–	25,620 kWh
Solar panels production	–	12,229 kWh (47.7%)
Wind turbine production	–	5,604 kWh (21.9%)
Energy purchased from grid	–	7,787 kWh (30.4%)
Energy consumed	–	55.6%
Energy wasted/sold to grid	–	44.4%
CO ₂ reduction	–	Up to 90%
Economic impact of energy	High cost	~50% savings, long-term economic benefit
Environmental impact	Harmful	Clean, sustainable energy, improved air quality

Table 20
Comparative analysis of PV–wind–grid hybrid system optimization models and economic indicators

No	System configuration	Optimization model	COE (\$/kWh)	NPC (\$)
Current study	PV + Wind + Grid	HOMER & PVsyst	0.0213	~ \$8357
[42]	PV+Wind+BT	HOMER	0.595	693,114
[43]	PV + Wind + BT	HOMER	0.363	319,132
[44]	PV + Wind + DG + Battery (remote off-grid)	HOMER Pro + MATLAB dispatch	0.15	16,400,000
[45]	PV+DG+BT	Numerical	1.006	8,757.8
[46]	PV + WT + DG + Battery (rural clinic system)	HOMER	0.103	109,307
[30]	Grid-connected PV + Wind hybrid	HOMER	~0.090	~96,900
[37]	Grid + Wind + PV + Diesel G	HOMER	0.0172	50592.16

5. Conclusions and Future Work

The main contributions of this study can be summarized as follows:

- 1) Development of a battery-free hybrid PV/wind/grid system optimized using HOMER and PVsyst.
- 2) Quantitative economic evaluation including NPC, LCOE, IRR, and payback period.
- 3) Demonstration of up to 90% emission reduction for small commercial units.
- 4) Provision of a scalable clean-energy framework for developing urban areas.

This study shows that a PV/wind/grid hybrid system for bakeries in a representative urban region of Afghanistan is technically reliable, economically viable, and environmentally sustainable. It fully meets the annual energy demand (13,908 kWh) while producing 25,620 kWh/year, with ~70% from renewables. Solar contributes 47.7%, wind contributes 21.9%, and excess energy (11,412 kWh) can be exported to the grid.

Economically, the system has an NPC of \$8357, an LCOE of \$0.0213/kWh, and a short payback of 2.28 years—cutting energy costs by ~55% compared to gas-based systems. Environmentally, CO₂ emissions drop by up to 90%, with major reductions in other pollutants.

This research combines HOMER Pro and PVsyst for simultaneous optimization, applies the model specifically to small urban bakeries in Afghanistan, and quantifies clear environmental and economic benefits.

Hybrid renewable systems can replace conventional fuel-based energy in small commercial units, offering a scalable, clean, and cost-effective solution for developing countries.

Future research could explore the integration of battery energy storage systems with the PV/wind/grid hybrid setup to further enhance energy reliability and reduce dependence on the grid. Advanced energy management strategies, such as predictive load control and real-time optimization, could be implemented to improve system efficiency and minimize energy wastage, especially during periods of high renewable generation. Additionally, testing the system under varying seasonal and extreme weather conditions in a representative urban region of Afghanistan would provide more robust performance data and improve long-term operational planning.

Another direction for future work involves scaling this model to other small urban commercial sectors, such as small shops, restaurants, or workshops, to evaluate its adaptability and economic feasibility. Life-cycle assessments could be performed to quantify environmental impacts more precisely, including the embedded energy and carbon footprint of system components. Finally, policy and incentive analysis could be conducted to identify the most effective strategies for promoting hybrid renewable energy adoption in Afghanistan's urban commercial sector.

Recommendations

From a policy perspective, the findings of this study provide valuable insights for government institutions and energy regulators. It is recommended that local authorities support the adoption of hybrid PV/wind/grid systems in small and medium-sized enterprises through net-metering expansion, low-interest loans, and financial incentives. Integrating such hybrid renewable energy solutions into national energy strategies can play a vital role in achieving sustainable urban development, reducing fuel

dependency, and meeting climate mitigation goals. It is recommended that local authorities and energy policymakers support the implementation of hybrid PV/wind/grid systems in small commercial units through financial incentives, low-interest loans, and net-metering expansion.

Future studies should investigate the integration of battery storage and intelligent energy management systems to further enhance reliability, reduce grid dependency, and optimize system performance.

The proposed hybrid model should be replicated in other cities and small-scale industries to evaluate its scalability and contribution to national energy sustainability and emission reduction targets.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data are available from the corresponding author upon reasonable request.

Author Contribution Statement

Massoud Danishmal: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Dost Mohammad Sarwari:** Writing – review & editing, Resources. **Mohammad Yasin Kamaly:** Writing – review & editing. **Mohammad Adel Adeel:** Writing – review & editing. **Atiqullah Hamim:** Writing – review & editing.

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