Journal of Energy and Safety Technology

JEST

RESEARCH ARTICLE Open Access

ECONOMIC INVESTIGATION AND PERFORMANCE EVALUATION OF AN INSTALLED HYBRID PV/BATTERY SYSTEM IN NAJAF CITY, IRAQ

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Article History

Received:	Received in revised form:	Accepted:	Published:
June 10, 2025	August 24, 2025	September 17, 2025	December 12, 2025

Abstract

Iraq experiences chronic electricity shortages despite having abundant solar energy potential, with most cities receiving utility power for less than 15 hours per day. To mitigate reliance on expensive and polluting private generators, this study evaluates the performance and cost-effectiveness of a residential hybrid photovoltaic (PV)/battery system in Najaf City. The research aims to assess the technical, economic, and environmental feasibility of the system, focusing on its ability to supply electricity during both grid-connected and blackout periods. A 5.7 kW PV system integrated with a lithium battery storage unit and smart inverter was installed at a household site. Load estimation, system design, and component specification were conducted based on actual consumption patterns. HOMER Pro software was used to simulate performance data, solar irradiance, and temperature profiles. Cost comparisons were made between the hybrid system and private diesel generators over a 20-year project lifespan. The results demonstrated that the PV/battery system generated more electricity than consumed, with a total production of 5.85 MWh compared to 5.55 MWh of usage over a 7-month period. The system reduced CO_2 emissions by 3.14 tons and offered significant economic savings. While the private generator's projected cost was USD 13,420, the hybrid system cost only USD 9,088 under normal conditions or USD 11,488 in worst-case scenarios, representing up to 40% in savings. Payback period analysis showed a return on investment within 3 years for normal conditions or 6 years for worst conditions. Compared to previous studies that primarily relied on simulations, this research uniquely incorporates real-world performance data from an operational system, offering empirical validation of technical and economic viability. The significance of this study highlights the practical effectiveness and financial attractiveness of hybrid PV/battery systems for residential use in Iraq and similar regions with frequent power outages. Adoption of such systems can support national sustainability goals, reduce dependency on fossil fuels, and promote cleaner energy access for communities.

Keywords: solar photovoltaics; hybrid system; diesel; HOMER; IRAQ.

1.0 INTRODUCTION

Worldwide, the main considerable energy source for generating electricity is fossil fuel. This form of energy is under critical depletion issue for many countries. As a solution, sustainable and renewable energy sources (RES) such as wind, solar, geothermal, tidal, biomass, etc. considered as the most desired sources for clean power generation. Recently, the RES takes great attention as a powerful replacement for electricity generation. Most of the developing and even undeveloped countries have adapt various technologies for different forms of RES for power generation, mostly electricity [1-3].

RES hold substantial promise for success in developing nations, particularly in regions where a significant portion of the population lacks reliable access to electricity or lives in areas with limited power supply. Unfortunately, in Iraq electricity is facing a series of significant challenges by force. Since the disruption and overall ruin, which first began in 1991, there was and still an electricity outage. In recent years, Iraq has shown developments in enhancing its generation capacity, leading to a rise in electricity production from 5 GW in 2005 to meet 14 GW in 2016 as a peak demand. Yet, electricity industry continues to face significant challenges such as extensive distribution and transmission losses, along with a yearly demand escalation exceeding 10 %. In spite of the great growing of investments in the electrical district and the generation size, only 15 hours per day the utility grid supplies electricity to consumers. Almost the rest of hours of the day are supplied by private generators [4-7].

Figure 1 shows the percentage of current generation mix in Iraq. The highest source of electricity generation is from gas turbines, sharing about 48% of the total generation, tailed by the oil power sector that produces about 30%. The residual portion of the power supply is provided from hydroelectric plants and diesel generators, constituting 14% and 8% of the total share, respectively [8].

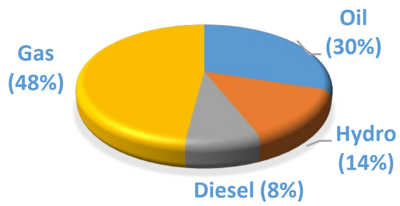

Figure 1: Iraq electricity generation profile [8].

Iraq has more than 3000 hours of clear sunshine light per year, which consider as an enormous amounts of direct solar radiation to be received. The rate of the global solar radiation on the horizontal surface in Iraq is approximated at (5-5.6) kWh/m²/day. The average sunshine hours at a day are about 7 to 8 hours at winter time and increased to nearly 11 to 12 hours at summer time. In addition, Iraq has more than 3600 hours sun duration in a year as the weather data shown in Figure 2. A 1750 to 2200 kWh/m^2/year is the average solar radiation in Iraq. Many countries globally receive fewer hours of sunlight each day compared to the data recorded in Iraq [9].

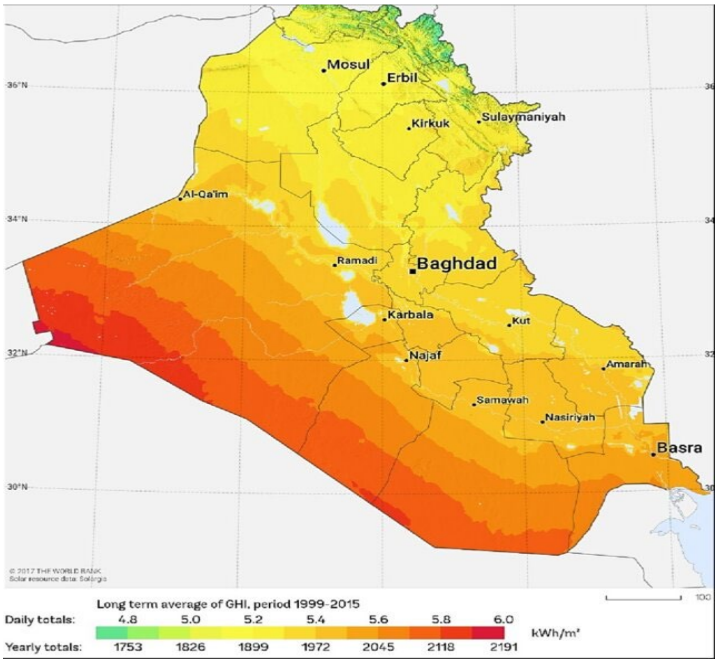

Figure 2: Horizontal solar radiation in Iraq (kW/m²) [9].

Over the years, numerous significant initiatives have been implemented worldwide to expand public electricity infrastructure through the installation of grid-connected PV systems. These systems not only generate clean electricity and deliver environmental benefits by reducing greenhouse gas (GHG) emissions [10], but also provide advantages to consumers in certain countries, such as the ability to sell surplus electricity back to the utility grid. Recently, the Iraqi government's accession to the Paris Climate Agreement has opened opportunities to promote both small- and large-scale electricity generation from renewable energy resources available in Iraq [11].

The deployment of grid-connected PV systems has demonstrated itself as an appealing and efficient energy supply solution globally. The integration of PV systems with the utility grid is experiencing substantial growth in numerous developing nations, including those with limited resources. Many studies have examined the planning and implementation of on-grid PV systems, but some have only addressed grid-connected systems that consist solely of PV panels without energy storage.

In Ref. [11], the authors investigated the solar/wind hybrid system for generating electricity in Duhok city. The evaluation and optimization of the system were done for both grid-connected and standalone system. The results simulated using HOMER software of the proposed system which has proved that hybrid grid-connected system is the most cost effective than the off-grid design model for the similar load. Were the cost of electricity found to be 0.0618 $/kWh, which is much cheaper compared to Duhok residential power grid of 0.1$/kWh.

In Ref. [12], authors presented a study for the feasibility of using flat-plate solar collector for heat generation in purpose of reducing electrical consumption from the utility grid and generating the required heating system which has conducted in Baghdad city. The investigation of the experimental study was applied for three houses of different models. Regarding the great benefit of Iraq climate, free heating would be suitable to use for both domestically and commercial fields to share the reduction in electricity usage from the national grid as the study has approved.

In Ref. [2], a case study of constructing a 10 MW sun-tracking PV system in Iraq has been done. This research aims to study the economic and environmental perspective for three different PV panel installation systems, fixed, single-axis and dual-axis tracking systems for Al-Anbar city. The results show that the region has a very promising income for solar PV system investment in production of electric power where the dual-axis tracking system has the best economical results among other systems. Beside these economic parameters such as cost of energy, cash flow and net present values, the reduction of the amount of greenhouse gas emissions has been presented.

In Ref. [1], a residential customer in Baghdad city has been chosen for investigating the analysis of the technological, economic, and environmental aspects of grid-connected PV system and HOMER software was used for this analysis. The results shows that when national grid is used to recharge the batteries at any rate beside the PV system to provide electricity due to the outage times was the best performance.

In Ref. [13], in different sectors of Iraq country, a PV system and net metering mechanism for developing a financial model was considered in this study. The results revealed that, when applying a net metering system beside the installed PV system, it showed much more feasibility regarding the considered economic parameters in the commercial sector. It is important to consider an increment in the electricity tariff for attracting such investments. Also, the findings indicated that as much more increment in the capacity of the installed PV system in both residential and commercial buildings this would result in a beneficial return on investments.

In Ref. [14], another economic study for evaluating the PV system has been established here where the parameters such initial cost, annual income, lifecycle cost and payback period were taken into consideration. As a comparison to conventional source (gasoline), the results show that the PV system is much cheaper when lifecycle cost is taken into account and this result was found is due to the high cost of fuel during the period of 20-years. It approves that the usage of PV system instead of conventional fuel for electricity generation in Iraq is much feasible to apply beside it considered as environmentally friendly energy production.

This study addresses a critical gap in Iraq's electricity sector by demonstrating the techno-economic feasibility of hybrid PV/battery systems for residential applications. Unlike prior works that mainly evaluated standalone PV or grid-connected configurations, this research focuses on integrating battery storage to ensure reliable supply during frequent grid blackouts. In Iraq, where electricity shortages are often mitigated through costly and polluting private diesel generators, this study highlights hybrid PV/battery systems as a cleaner and more cost-effective alternative. By providing empirical evidence from a real-world case in Najaf city, the findings not only validate the system's economic competitiveness but also offer practical insights for scaling decentralized renewable solutions in energy-insecure regions. Furthermore, the results contribute to academic discourse by filling the knowledge gap on hybrid solar-battery applications in conflict-affected developing countries, while offering policymakers and stakeholders a replicable model to reduce diesel dependency, enhance energy resilience, and advance progress toward national sustainable development goals.

2.0 METHODOLOGY

This section outlines the methodology employed to evaluate the technical, economic, and environmental performance of an installed 5.7 kW residential hybrid PV/battery system in Najaf City, Iraq. The methodology encompasses input data and climate analysis, system configuration, design specifications, and cost assessment. Both simulated and real-time data were used to perform comparative analyses of system performance, capital and operational costs, and environmental benefits. Additionally, mathematical models and software tools, including HOMER Pro, were utilized to optimize system design and assess its feasibility under local climatic and load conditions.

2.1 Input data 1: Load estimation

Reliable estimation of the household load profile is critical for accurately sizing and evaluating the performance of a hybrid PV/battery system. In the context of Iraq, where electricity supply from the national utility grid is intermittent, residential consumers typically receive power for approximately 15 hours per day [1], with the remaining hours supplemented by private diesel generators or other alternative sources.

This study focuses on a residential household located in Al-Najaf City (32°1.9'N, 44°19.3'E), where electricity outages follow a non-continuous pattern throughout the day, often alternating between utility supply and generator-based power in two-hour intervals.

To capture realistic energy consumption, a detailed inventory of electrical appliances was compiled, including their rated power, quantity, and average daily operating hours. Table 1 summarizes the key electrical loads within the household, which collectively result in a total connected load of 3.84 kW and a daily energy consumption of approximately 47.73 kWh. The predominant loads include an air conditioner (3.0 kW), a refrigerator (0.6 kW operating continuously), LED lighting, and ceiling fans. Figure 3 depicts the load profile for the studied household. This load profile was selected to represent the typical energy demand of a residential house in Iraq.

To ensure system reliability and account for real-world inefficiencies such as panel orientation, dust, and temperature losses, the hybrid PV system was oversized by a factor of 1.3. The application of a 1.3–1.5 oversizing factor in PV system design is critical to account for real-world inefficiencies, including energy losses from dust accumulation, temperature derating, module degradation, and unpredictable load variations. Recent studies in arid climates, such as Iraq, demonstrate that systems designed without such safety margins can underperform by 20–30% during peak demand or prolonged blackouts. By applying this multiplier, the proposed hybrid PV system ensures reliable energy supply while maintaining cost-effectiveness compared to diesel generators, as evidenced by empirical data from similar off-grid applications [15]. Therefore, while the nominal household load is 3.84 kW, the installed PV system capacity was set to 5.7 kW to maintain consistent energy supply during peak demand and suboptimal solar conditions.

Table 1: Typical Residential (house) Load Profile in Iraq

Items	The Power (W)	Number of Items	Operating Hours on Daily Basis	The Load (Wh/day)
Refrigerator	600	1	24	14400
Air Conditioner	3000	1	10	30000
LED Light	10	9	12	1080
Ceiling Fan	50	3	15	2250
Total	3840	-	-	47730

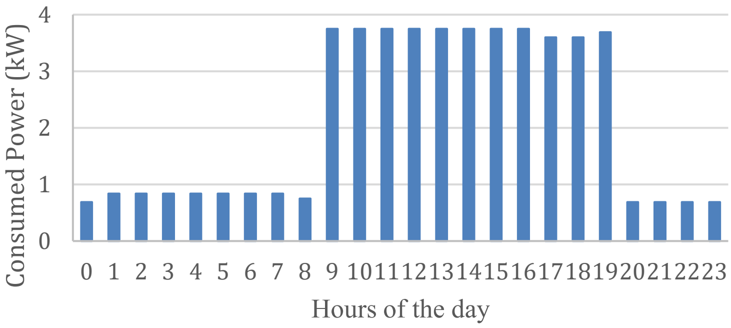

Figure 3: Typical Load Profile for the Residential House in Iraq

2.2 Input Data 2: Climate Data

The amount of solar radiation directed on PV panels and the ambient temperature both play an important role in the approximation of the output power of PV. Accordingly, the monthly average solar radiation and ambient temperature are provided by NASA through HOMER Pro software. The resulting hourly and monthly load profiles that were simulated using HOMER Pro software, as shown in Figures 4 and 5. These profiles provide critical inputs for system design optimization, ensuring the hybrid system can adequately support the household's energy demand during both grid-connected and blackout periods.

In Figure 3, it also illustrates the monthly average clearness index alongside solar radiation data for the selected site. The global horizontal solar radiation varies between 3 kWh/m²/day and 8 kWh/m²/day, with a scaled annual average of 5.5 kWh/m²/day. The figure clearly indicates that the peak solar radiation values were recorded in June, while December marked the lowest levels. In comparison to other regions worldwide, the solar radiation levels observed in this area are above average, presenting significant potential for the implementation of PV technology.

The performance of PV panels is significantly affected by ambient temperatures; thus, obtaining precise measurements of these temperatures is crucial. As depicted in Figure 5, the highest ambient temperature was typically recorded during the summer months (particularly in July), averaging 36.9°C. In contrast, the lowest temperatures occur in January, averaging 9.4°C. Notably, the annual average ambient temperature stands at 23.97°C [16-17].

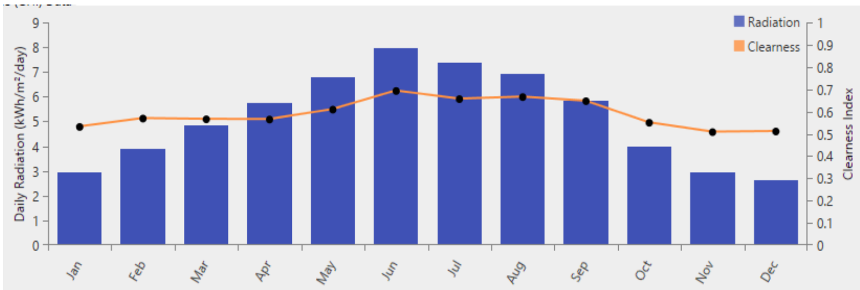

Figure 4: The global solar radiation of all months of the year [16,17].

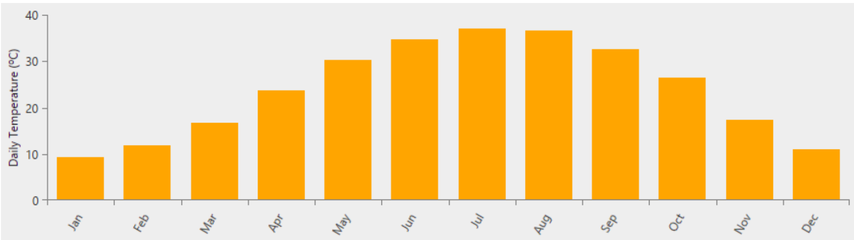

Figure 5: Yearly ambient temperature recorded for Najaf city [16,17].

2.3 Design specifications

The hybrid PV system installed for this study consists of three main components: PV panels, a hybrid inverter, and a battery storage unit. The system was designed to ensure reliable energy supply during both grid-connected and blackout periods. Each component was selected based on technical suitability, efficiency, and local availability, with specifications optimized to meet the estimated residential load. Figure 6 shows the schematic diagram of the proposed stand-alone solar system, simulated using HOMER software.

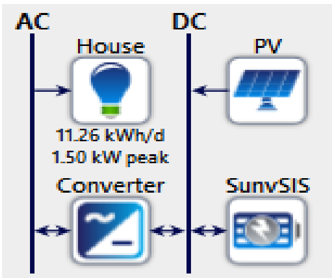

Figure 6: Schematic diagram for the stand-alone solar energy system by HOMER Pro software.

2.3.1 PV panels

Table 2 lists the specification details for the selected PV panels under this study. The PV array comprises ten fixed-mount panels rated at 570 W each, yielding a total installed capacity of 5.7 kW. These panels operate with an efficiency of 25.5% and can withstand a wide range of environmental conditions, with an operating temperature range of -40°C to 85°C. The panels are expected to maintain performance over a 25 years lifespan.

Table 2: The cost and technical parameters of the PV module used under this study [18]

Parameters	Value
Tracking system	Fixed
Module efficiency	25.5%
Maximum rated power (P_{max})	570W

Operating temperature	-40ºC ~ 85ºC
Voltage at P_{max}	43.55V
Current at P_{max}	13.09A
Operating and maintenance cost	$ 10/kW/year
Price of one panel	110 USD
Capital cost	$ 193/kW
Replacement cost	$ 193/kW
Lifetime	25 years

2.3.2 Inverter

The inverter is a critical component of the hybrid PV system, responsible for converting the direct current (DC) electricity generated by the solar panels into alternating current (AC) for household use. In this study, a modern hybrid inverter, featuring an integrated "All-in-One" configuration, was selected to enhance system reliability and operational flexibility. This unit combines a single-phase inverter with battery management functionality into a single, compact, and portable unit.

Designed for residential applications, the inverter offers a rated power output of 6 kW and a maximum PV input power of 7,800 W, supporting a PV input current of up to 26 A. It features a wide MPPT voltage range (150 – 425 V_{DC}), enabling efficient power harvesting across varying solar irradiance conditions. With a high conversion efficiency of 97.6%, the inverter ensures minimal energy losses during operation.

The unit includes advanced features such as dual output capability for intelligent load management, built-in Wi-Fi for real-time system monitoring via a dedicated mobile application, and an interactive LCD touchscreen for easy user control. Users can configure the operational priority of energy sources (PV, battery, or grid) and customize charging voltage and current settings according to load requirements.

Additionally, the inverter is equipped with grid-feed functionality, allowing excess solar energy to be injected into the utility grid, subject to local regulatory permissions. Its intelligent control system supports multiple modes of operation, including hybrid, on-grid, and off-grid configurations, making it adaptable to a wide range of use scenarios. Given its combination of functionality, efficiency, and user-friendliness, the inverter serves as the central management unit or "brain" of the hybrid energy system. The detailed technical specifications and cost breakdown are provided in Table 3 [18].

Table 3: The cost and technical parameters of the converter [18].

Parameters	Value
Rated Power	6kW
Maximum efficiency	97.6%
Battery nominal voltage	48 V_{DC}
MPPT voltage range	150-425 V_{DC}
Rated PV Input Voltage (V_{DC})	370 (125~500)
Max. PV Input Power	7800 W
Capital cost	$ 1000
Replacement cost	$ 1000
Operating and maintenance cost	$ 20/kW/year
Lifetime	10 years

2.3.3 Battery

The battery unit is an essential component of the installed hybrid system, serving as the storage medium for excess electricity generated by the PV panels and, when necessary, by the utility grid. A high-quality lithium iron phosphate ($LiFePO_4$) battery was selected for its superior performance and long lifespan. Each battery unit that rated at 100Ah was selected and is projected capable of withstanding over 6,000 charge-discharge cycles at a 90% depth of discharge. Two such units are installed, providing a combined storage capacity of 200Ah.

During off-grid periods, the battery system can supply a 60A load for one hour, 30A for two hours, 20A for three hours, or 15A for four hours, depending on the demand. For optimal operation under typical household consumption, the system is ideally configured to deliver a 10A load continuously for up to six hours. The detailed specifications of the selected batteries are presented in Table 4 [18].

Table 4: The cost and technical parameters of the battery [18].

The Parameters	Values
Nominal voltage	51.2V
Nominal capacity	5.12kWh
DOD	90%
Capital cost (200Ah - 2 units)	$ 2400
Replacement cost (200Ah - 2 units)	$ 2400
Operating and maintenance cost	$ 5/kW/year
Lifetime	10 years
Operating Temperature Range	Charge: 0～55℃/ Discharge: -20℃～+55℃
Life Cycle	≥6000

2.3.4 Grid

The primary source of electrical energy for the household is the national utility grid. During periods when the grid is unavailable (typically during daytime outages), the installed PV system supplies the load directly. If the PV generation is insufficient or unavailable, the charged battery system serves as the backup to meet the household demand.

Currently, Iraq does not implement Feed-in Tariff (FiT) or Net Metering mechanisms. As a result, the smart inverter prioritizes battery charging with any surplus energy generated by the PV system. Once the battery is fully charged, the remaining excess energy is exported to the utility grid without financial compensation. However, the inverter settings allow users to disable grid feed-in if desired. It is anticipated that in the near future, regulatory frameworks such as net metering will be introduced to incentivize renewable energy adoption and reward surplus energy contribution.

In this study, the cost of electricity drawn from the grid is not included in the financial analysis, as the utility remains the default supply whenever available. Instead, the economic comparison focuses solely on the costs of the installed PV/battery system relative to the continued use of private diesel generators over the project's 20-years lifetime.

3.0 RESULTS AND DISCUSSIONS

This section presents and discusses the key findings obtained from the performance evaluation and cost analysis of the installed hybrid PV/battery system in Najaf City, Iraq, simulated by HOMER Software. The results are organized into several subsections, covering costs of electricity from private generator, cost of the installed PV system, economic feasibility, environmental impact, and system payback period. Both simulated and recorded data are analyzed to assess the system's ability to meet residential energy demand, reduce reliance on private generators, and contribute to long-term sustainability. The analysis also includes a comparison of system performance across different months, reflecting seasonal variation in solar resource availability. The following subsections provide a detailed examination of these aspects.

3.1 Cost of electricity from Private Generator

In Al-Najaf City, Iraq, private diesel generators are widely used to supply electricity during periods of grid outages. The cost of electricity from these generators varies throughout the year, with significantly higher rates observed during the summer months due to increased demand and operating costs. Typically, the cost per ampere (A) ranges from USD 2 to USD 5 in winter, while in summer it increases to between USD 7 and USD 11, as shown in Table 5. These values are calculated based on an average exchange rate of 1 USD = 1,500 Iraqi Dinar [18]. According to [18], the average monthly cost of private generators is provided per 1A load. For the annual cost estimation, Al-Najaf City was assumed to use an average load of 10A. Based on the reported exchange rate and generator costs, the annual expenditure for an average 10A load in Al-Najaf City is estimated at USD 671.

Table 5: The cost of the private generators during the months of the year [18]

Months	Cost of 1A (USD)	Cost of 10 A load
January	3.3	33
February	3.3	33
March	3.3	33
April	4	40
May	4	40
June	11.3	113

July	11.3	113
August	11.3	113
September	4	40
October	4	40
November	4	40
December	3.3	33
Total	67.1	671

To evaluate the economic impact over the lifetime of the project, the cost of operating a 10A load using private generators was calculated on a monthly basis and extrapolated over a 20-year period. The total annual cost for a 10A load amounts to USD 671. Consequently, the cumulative cost over 20-years is:

Total cost of private generators for 10A (20-years)
= 20 years *(33+33+33+40+40+113+113+113+40+40+40+33) = 20*671= USD 13,420.00

This figure represents the baseline cost (USD 13,420) of meeting blackout demand using conventional private generation for a household with an approximate 5 kW load. It provides a critical reference point for comparison against the installed hybrid PV/battery system.

3.2 Cost of the installed PV system

This section outlines the cost structure of the installed 5.7 kW hybrid PV/battery system designed to support a residential load of approximately 10A during grid blackout periods. The cost details for all system components, excluding installation fees, were obtained from a local solar energy provider in Najaf City [18]. Table 6 presents the breakdown of equipment types, sizes, quantities, and associated lifespans.

Table 6: The cost and type of all items needed for the installed system.

Items	Size	Cost (USD)/Piece	Numbers	Lifetime
PV Panels	570 W	110	10	20
Converter	6 kW	1000	1	10
Battery	100Ah	1200	2	10 Years
Ironwork	-	520	-	20
Wiring and other requirements	-	334	-	10

Since the lifetime of the PV panels is 20 years, they are not expected to require replacement within the 20-year study period. In contrast, the inverter has a lifetime of 10 years; therefore, it must be replaced once during the project horizon, resulting in two units being considered in the cost calculation. Similarly, both the batteries (10-year lifetime) and the wiring/other requirements (10-year lifetime) also require replacement once within the 20-year period.

The total system cost over a 20-year project lifespan is calculated as follows:

Total cost = $(\text{PV unit} * \text{cost})_{20\text{-year}}$ + $(\text{Inverter unit} * \text{cost})_{20\text{-year}}$ + $(\text{Battery unit} * \text{cost})_{20\text{-year}}$ + $(\text{Ironwork cost})_{20\text{-year}}$ + $(\text{wiring cost})_{20\text{-year}}$
= (10 * 110) + (2 * 1000) + (2 * 2 * 1200) + 520 + (2* 334) = USD 9, 088

Compared to the projected 20-year cost of using private generators (USD 13,420), the installed PV system offers nearly 40% cost savings, making it a financially viable alternative for residential electricity supply.

To account for a worst-case scenario, it is assumed that the batteries may require replacement every 7 years due to accelerated wear from frequent charge-discharge cycles. Under this condition, the batteries would need to be replaced twice (total of four units over 20-years), resulting in:

Adjusted total cost = (10 * 110) + (2 * 1000) + (2 * 3 * 1200) + 520 + (2* 334) = USD 11,488

Even under this conservative estimate, the hybrid PV system remains approximately 20% cheaper than continued reliance on private diesel generators. Additionally, if net metering or Feed-in Tariff (FiT) mechanisms are introduced in the future, the system's cost-effectiveness would improve further through financial compensation for surplus energy exported to the grid.

The installed system, shown in Figure 6, is mounted on the rooftop of a residential building in Najaf. It comprises 10 units of PV panels (570W each), a 6kW hybrid inverter, and two 51.2V lithium battery units with a total storage capacity of 200 Ah. The technical specifications for each component were previously detailed in Section 2.3.

Figure 6: The installed PV/Battery/Inveter System [18].

3.3 Recorded data of the installed PV system

This section presents the operational data collected from the installed 5.7 kW hybrid PV system over a monitoring period from April to November 2024. The smart hybrid inverter continuously records system performance parameters, including PV power generation, electricity consumption, battery charging/discharging levels, and energy exchange with the utility grid. These data are logged on both hourly and monthly bases, as illustrated in Figure 7.

Figure 7 displays real-time data visualization, showing instantaneous PV output, battery charge status, system consumption, and grid interaction. This allows users to monitor system behavior, determine whether power is being drawn from or fed into the grid, and assess the system's overall operational state. The figure displays data recorded on 4 April 2024. According to the monitoring system, the PV system was generating 1.93 kW of power at that time. This energy was directed towards charging the battery, as indicated by the flow arrows, with the surplus exported to the utility grid. No electrical load was recorded within the household at that specific moment.

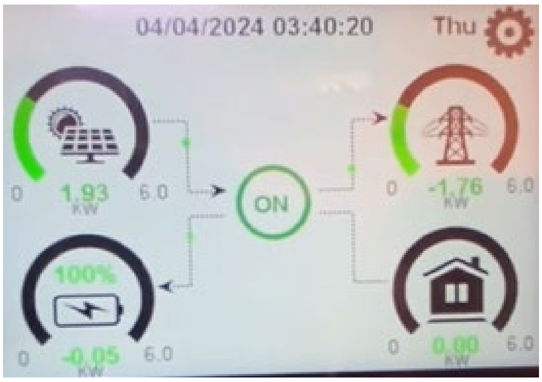

Figure 7: The instant data of the system [17].

Throughout the seven-month monitoring period, the system demonstrated a positive energy balance. As shown in Figure 8, the system generated a total of 5.85 MWh of electricity, slightly exceeding the consumption of 5.55 MWh. As can be observed, comparison of actual energy production (5.85 MWh) against consumption (5.55 MWh), demonstrating the system's practical effectiveness in meeting household demand and providing surplus energy, which supports the economic and environmental arguments presented in earlier sections.

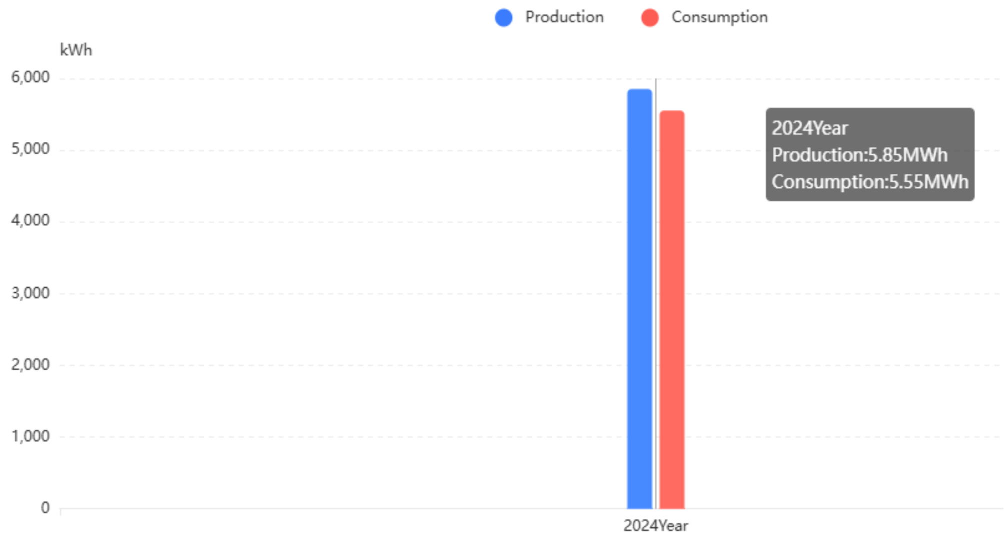

Figure 8: Total Production vs. Consumption (April–November 2024).

The daily generation data revealed that the highest single-day production occurred in May, reaching 36.6 kWh, while the lowest was in November, with only 24.7 kWh (see Figures 9 and 10). These fluctuations correspond to seasonal changes in solar irradiance and weather conditions. Figure 11 summarizes monthly production and consumption trends in 2024, where the highest monthly output (1.01 MWh) was recorded in July and the lowest (535 kWh) in September.

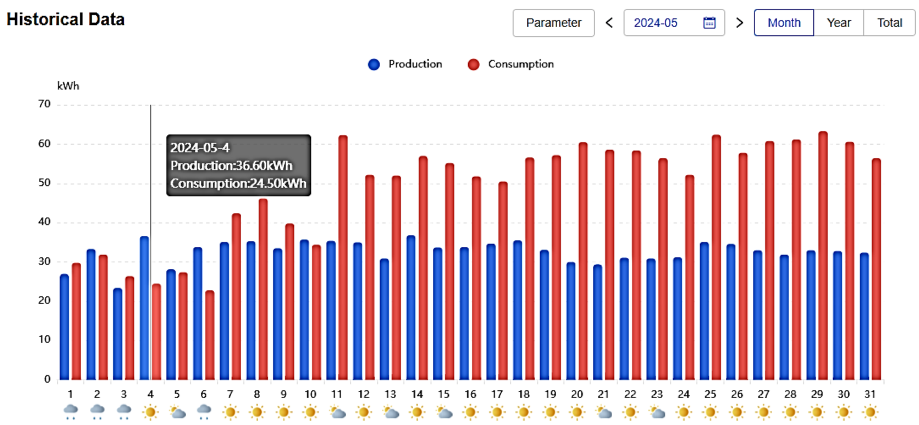

Figure 9: The daily energy trends in May 2024.

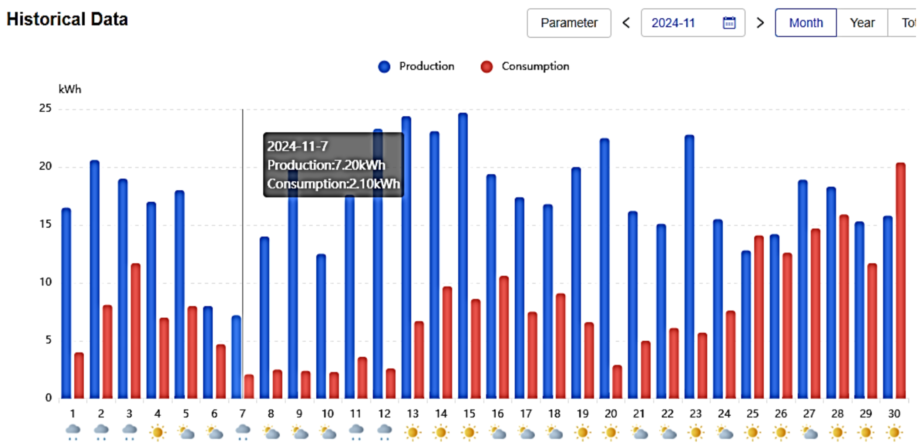

Figure 10: The daily energy trends in September 2024.

The highest recorded daily energy consumption occurred in June at 62 kWh, while the lowest was 2.1 kWh in November (Figure 12). Correspondingly, battery activity mirrored these trends. As seen in Figure 13, battery charging and discharging peaked in June at 413.6 kWh and 383.7 kWh respectively, while the lowest values were observed in November at 39.9 kWh and 28.6 kWh.

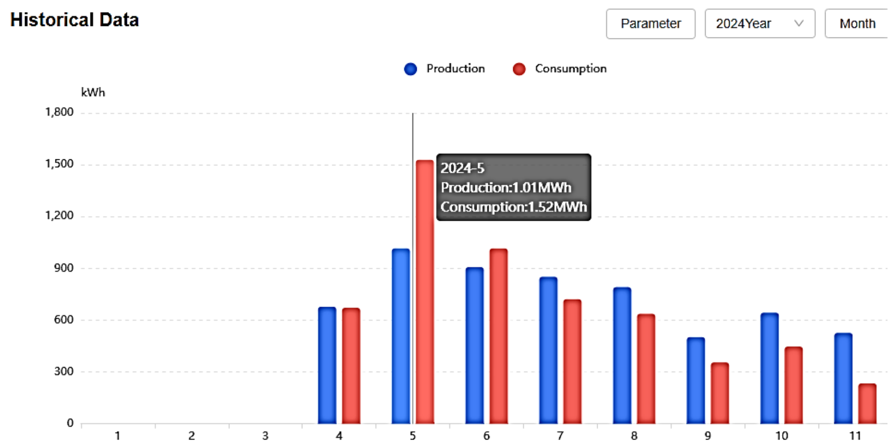

Figure 11: The monthly energy trends in 2024.

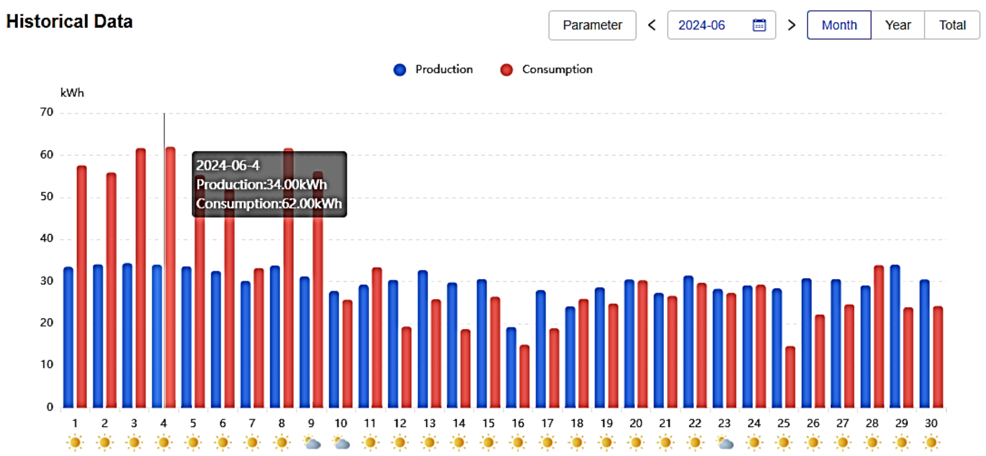

Figure 12: The daily energy production and consumption in June 2024.

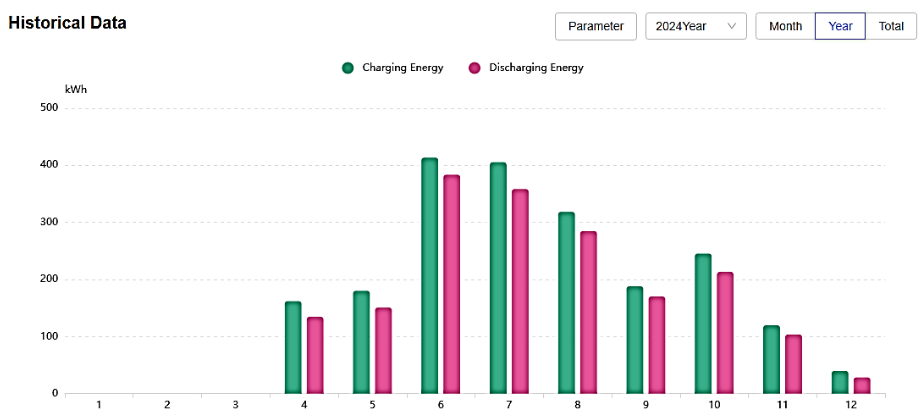

Figure 13: The battery activity.

Figure 14 presents a snapshot of the system interface, which displays real-time operational parameters such as current generation, battery status, grid usage, weather conditions, date, time, and solar cycle (sunrise/sunset). This user-friendly interface enhances system monitoring and energy management. The captured interface corresponds to a sunny day on 26 November, with an ambient temperature of 15 °C. The recorded sunrise and sunset times were 6:41 a.m. and 5:01 p.m., respectively. The interface also provides a three-day weather forecast. In terms of electrical performance, the PV system was generating 6 W at that moment. The remaining power demand was supplied by the utility grid at 5.54 kW, while the battery was concurrently charging and had reached a 73% state of charge. The instantaneous electrical load recorded at that time was 61 W.

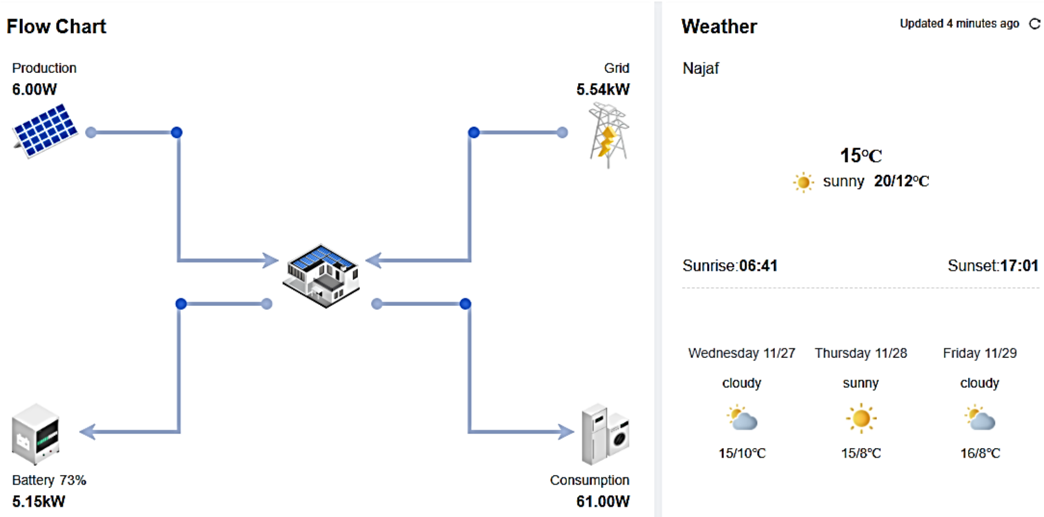

Figure 14: System Interface and Daily Snapshot.

Cumulatively, from installation to the end of November 2024 (a period of 232 days), the system produced a total of 3.97 MWh, with 2.4 MWh exported to the grid. Additionally, the system contributed to a reduction of approximately 3.14 tons of CO_2 emissions. Although excess energy is currently fed into the grid without compensation due to the absence of a net metering mechanism, the future implementation of such policies could further enhance the economic viability of similar systems. Recorded data confirming a surplus in energy production and significant CO_2 emissions reduction strongly support the argument for the economic and environmental viability of hybrid PV/battery systems, validating the simulations and theoretical claims presented earlier in the paper.

Figure 15 shows a typical daily record including hourly energy production, consumption, and grid activity, providing a comprehensive view of system behavior over a 24-hour cycle. As shown in the figure, the data was recorded on July 25, 2024. The 24-hour profile displays three key parameters: the red line represents power consumption, the blue line indicates power generation, and the green line shows the battery's State of Charge (SoC) throughout the day. In addition to the daily profile, the system provides a monthly summary of energy generation and consumption. During the month of November, the PV system produced a total of 458.5 kWh. Of this amount, 87.1 kWh was used to charge the battery, 0.5 kWh was consumed by the system itself (self-consumption), and 370.9 kWh was exported to the utility grid. On the consumption side, the total energy usage for November was 171.6 kWh, which comprised 0.5 kWh of system self-consumption, 87.1 kWh discharged from the battery, and 101.8 kWh purchased from the grid.

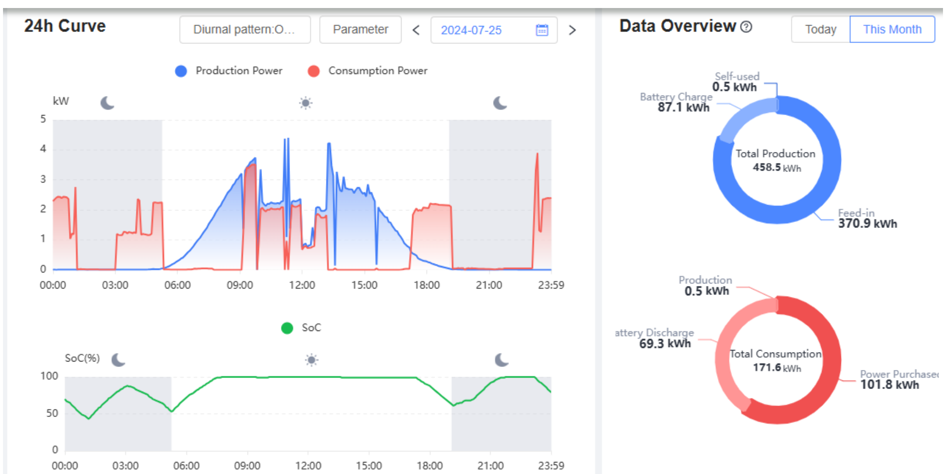

Figure 15: Daily System Performance Overview.

Lastly, Figure 16 illustrates the monthly summary of energy purchased from the grid and energy fed into it. May recorded the highest grid purchase (784.7 kWh), while November marked the lowest. Interestingly, July had the highest PV generation (470 kWh), whereas May had the lowest (242 kWh), further reinforcing the influence of seasonal variability.

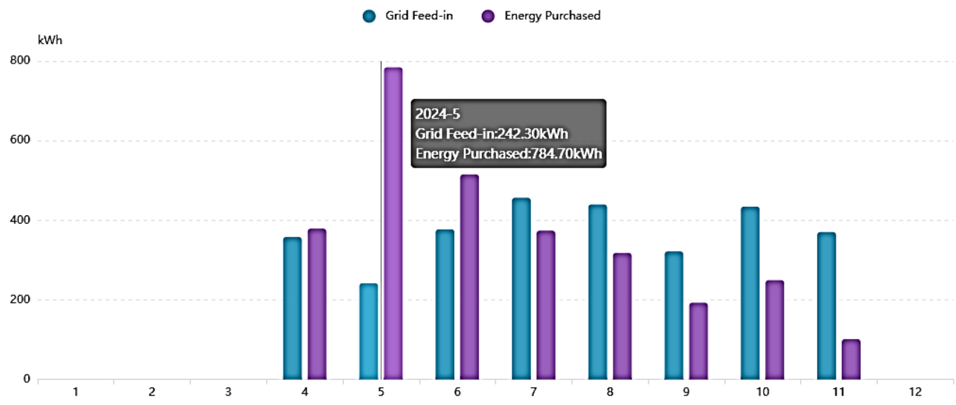

Figure 16: Monthly Grid Purchase and Feed-in Summary.

Thus, the recorded operational data presented in this section significantly enhance the credibility of the findings, providing empirical validation essential for stakeholders and decision-makers considering investments in hybrid renewable energy systems.

3.4 Payback period analysis

As discussed earlier, the total cost of the installed hybrid PV system over a 20-year project lifespan is estimated at USD 9,088 under normal operating conditions and USD 11,488 under a worst-case scenario (assuming more frequent battery replacements). In contrast, the projected cost of relying on private diesel generators for the same period is approximately USD 13,420. This results in an overall savings of USD 4,332 (normal case) or USD 1,932 (worst case). In case of deciding the most suitable payback period for residential consumers with long term project such as this with 20-years lifetime, is roughly from 6 to 10 years [19-22].

To evaluate the economic return, the annualized cost of the hybrid system for both normal and worst-case scenario is calculated as:

Annual System Cost $_{\text{(normal)}}$ = USD 9,088/20 years = 454.4 USD/year

Annual System Cost $_{\text{(worst)}}$ = USD 11, 488/20 years = 575 USD/year

Given that the equivalent annual expenditure on private generators is 13,420 USD/20 years = 671 USD/year, the annual savings from using the hybrid system amount to:

Annual Savings $_{\text{(normal)}}$ = 671 – 454.4 = USD 216.6

Annual Savings $_{\text{(worst)}}$ = 671 – 575 = USD 96

The payback period is then determined using the following equation:

$$Payback\ period\ (best) = \frac{Cost\ of\ investment}{additional\ yearly\ income} = \frac{575}{96} = 5.99 \cong 6 \text{ years}$$

$$Payback\ period\ (worst) = \frac{Cost\ of\ investment}{additional\ yearly\ income} = \frac{575}{216.6} = 2.65 \cong 3 \text{ years}$$

This result indicates that the system achieves full cost recovery in 3 and 6 years for normal and worst conditions, making it a highly attractive investment from both financial and energy security perspectives. Fluctuations in diesel prices, interest rates, and system degradation can significantly impact on the Levelized Cost of Energy (LCOE) and payback period of both PV and diesel systems. Rising diesel prices increase the LCOE of diesel generators, shortening the payback period for PV systems due to higher fuel cost savings. Conversely, higher interest rates raise financing costs, disproportionately affecting PV systems, which have higher upfront capital expenses, thus increasing their LCOE and extending their payback period. Additionally, PV system degradation over time reduces energy output, slightly increasing LCOE, while diesel generators face efficiency losses and maintenance costs, further elevating their operational expenses. These dynamic factors make PV systems more economically favorable when diesel prices are high but emphasize the need for stable financing and efficient maintenance to maximize long-term savings.

The findings of this study align with and extend the body of literature assessing the feasibility of PV systems in Iraq, particularly in urban areas such as [1, 2, 11–13]. For example, in Ref. [14], the authors evaluated a 2kW PV system in comparison with a 2.5kW gasoline generator. Their results demonstrated that, over a 20-year operational period, the PV system incurred less than half the total cost of the conventional generator. In addition to significant cost savings, the PV system offered considerable environmental advantages by avoiding greenhouse gas (GHG) emissions and reducing other air pollutants associated with fossil fuel combustion.

What distinguishes the present study from previous research is its incorporation of real-time recorded data from an installed hybrid PV/battery system operating under actual conditions in Najaf City. While earlier studies primarily relied on simulation models or assumed operating scenarios, this work offers empirical validation by analyzing system performance, consumption behavior, battery cycling, and grid interactions over a seven-month period. Furthermore, the economic analysis includes both best-case and worst-case battery replacement scenarios, providing a more comprehensive view of long-term viability.

Another unique contribution of this study is its emphasis on blackout mitigation in areas with irregular grid supply, which has not been as deeply explored in earlier works. By demonstrating that the system achieved a payback period of less than six year, this research provides stronger financial justification for household-scale PV adoption in regions with frequent electricity disruptions.

Overall, while prior studies have established the theoretical feasibility of PV systems in Iraq, this study provides practical, field-based evidence supporting the widespread deployment of hybrid solar technologies as a cost-effective and sustainable energy solution.

4.0 CONCLUSION

This study evaluated the techno-economic and environmental performance of an installed 5.7 kW hybrid PV/battery system for residential use in Najaf City, Iraq. The analysis was motivated by the chronic electricity shortages experienced across Iraq, where households typically receive limited hours of electricity from the national grid and rely heavily on expensive, polluting private generators. Leveraging Iraq's abundant solar irradiance, the proposed hybrid system integrates PV panels, lithium-ion batteries, and a smart inverter to ensure a stable and sustainable energy supply during both grid-connected and blackout periods. Real-time operational data recorded over a seven-month period confirmed the system's ability to consistently meet household energy demands while generating surplus electricity. The system also achieved a net reduction in greenhouse gas emissions of approximately 3.14 tons over eight months. From an economic perspective, the hybrid system proved significantly more cost-effective than continued reliance on private diesel generators. The total 20-years system cost was estimated at USD 9,088 under normal battery replacement assumptions and USD 11,488 under a worst-case scenario, both of which are lower than the USD 13,420 projected cost of private generator usage. The payback period was calculated to be 3 and 6 years for both normal and worst conditions, highlighting the system's strong return on investment. In comparison to previous studies, this research provides empirical validation through field-recorded data, enhancing the credibility and practical relevance of its findings. The results demonstrate that hybrid PV/battery systems represent a viable, clean, and economically attractive solution for enhancing energy security in regions with unreliable grid infrastructure. Overall, this study supports broader deployment of decentralized solar energy systems in Iraq and similar contexts, emphasizing their potential to reduce energy costs, improve reliability, and contribute to national sustainability goals.

Acknowledgements

The authors would like to express their sincere appreciation to Al-Furat Al-Awsat Technical University for fostering a strong research and publication culture among its academic community. Special thanks are extended to the Centre of Electrical Energy Systems (CEES), Institute of Future Energy, Universiti Teknologi Malaysia (UTM) and the Faculty of Electrical Engineering, UTM, University of Kufa Iraq and AL-Shams Solar Energy Company for their continuous support, encouragement, and provision of resources that have greatly facilitated the development of this book chapter.

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