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Research Article

Optimal Design of an Off-Grid Solar Energy System Integrated with a Diesel Generator for Urban Areas in Pakistan

Muhammad Kashif[*], **M. Tariq Iqbal**, **Mohsin Jamil**

Department of Electrical and Computer Engineering, Memorial University of Newfoundland, St. John's, NL, Canada
E-mail: mkashif22@mun.ca

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Abstract: The growing energy demand in Pakistan, coupled with the challenges posed by reliance on imported fossil fuels, necessitates the exploration of alternative energy solutions. This study presents the design and techno-economic analysis of an off-grid hybrid energy system tailored for a residential neighborhood in Karachi, Pakistan. The system integrates individual solar energy solutions for seven housles, supplemented by a shared diesel generator to ensure a reliable power supply, particularly during load-shedding and grid outages. The study utilizes HOMER Pro software to model and optimize various configurations, taking into account local solar insolation levels and seasonal variability in energy demands. The optimized system includes photovoltaic (PV) panels, battery storage, and a shared diesel generator with individual connections and meters, with each house receiving a customized solution based on its specific energy requirements, ranging from 15 kWh/day to 45 kWh/day. The shared diesel generator is designed to reduce the need for large battery banks, thereby minimizing both capital and operational costs. The results demonstrate a cost-effective solution with a Levelized Cost of Energy (LCOE) of $0.2959/kWh and a Net Present Cost (NPC) of $15,562.55 over a 25-year period. This research highlights the potential for implementing such systems in urban areas of Pakistan, offering a sustainable, reliable, and economically viable alternative to conventional energy sources.

***Keywords*:** solar energy, hybrid power systems, HOMER Pro, optimization, diesel generator, NPC, LCOE

1. Introduction

Energy is fundamental to the social and economic stability of any nation. In developing countries such as Pakistan, the demand for energy is driven by industrial development, modernization, and population growth. The International Energy Agency (IEA) projects a global increase in energy consumption by 1000 TWh annually to meet this growing demand [1]. However, Pakistan's heavy reliance on imported fossil fuels places significant strain on its foreign reserves, exacerbating a circular debt crisis. Substantial portions of the national budget are allocated to oil imports, further undermining the country's financial stability [2].

Fossil fuels are the predominant source of electricity generation worldwide, but their use presents significant challenges, including the depletion of conventional fuel reserves and environmental degradation. The reliance on non-renewable resources such as coal, oil, and natural gas results in substantial greenhouse gas emissions, contributing to climate change. In developing countries like Pakistan, this dependence exacerbates financial and environmental issues, as large portions of the budget are allocated to importing these fuels, straining the economy and increasing costs for end-users [3]. The

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Pakistani government frequently relies on loans from the International Monetary Fund (IMF), which impose stringent conditions, including the elimination of subsidies that once alleviated the financial burden on citizens. Consequently, consumers are confronted with elevated electricity costs exacerbated by a devalued rupee and a plethora of additional taxes [4, 5]. Moreover, the burden is intensified by the financial obligations towards Independent Power Projects (IPPs), which media reports suggest may be affected by corruption. These projects, acquired by previous administrations at inflated capacities, require rental payments regardless of actual electricity production, further straining the economic resources of the country [2, 6].

In light of the growing energy challenges, Pakistan urgently needs reliable and affordable energy sources to meet the population's demands and withstand extreme weather conditions. Solar energy has emerged as a particularly promising solution, given Pakistan's favorable climatic conditions, including an average of 8 to 9 h of sunlight daily and solar radiation levels ranging from 4 to 7 kWh/m^2/day [7].

In Pakistan, two types of solar energy systems have gained popularity: off-grid and on-grid systems. The on-grid system initially attracted widespread attention due to its simplicity and the introduction of net metering tariffs by NEPRA in 2015. Under this scheme, electricity generated by individual consumers and small businesses was bought back by the government at the same rate, making the system economically attractive. This led to significant savings for users and stimulated the market for on-grid systems [8]. However, recent changes in government policy, including the reduction of net metering benefits and the imposition of additional taxes on these systems, have diminished their appeal [9]. Moreover, on-grid systems have a notable drawback: the anti-islanding feature in grid-tied inverters prevents power supply during grid outages or load-shedding, which are frequent issues across Pakistan, thereby limiting the system's reliability.

In contrast, off-grid systems have become increasingly popular as a means to avoid government taxes and regulations associated with on-grid systems. However, the current state of battery technology makes these systems costly and often unaffordable for providing backup power throughout the night. To address this issue and offer a more sustainable and affordable solution, an off-grid system combined with a diesel generator has been designed. This system eliminates reliance on the grid, thereby avoiding high government taxes, and ensures uninterrupted power supply during load-shedding and outages without requiring a prohibitively large battery backup. This design offers a practical and independent energy solution that is both affordable for consumers and presents a lucrative opportunity for entrepreneurs in Pakistan.

2. Literature review

Extensive research has explored the viability of solar energy systems as sustainable solutions to various energy challenges. This review focuses on studies and systems tailored specifically for Pakistan and similar regions, analyzing the implementation of diverse photovoltaic (PV) and solar technologies. Manoo et al. [10], conducted a comparative analysis of on-grid and off-grid hybrid energy systems in District Jamshoro, Sindh, Pakistan. The study assessed the techno-economic viability of integrating solar, wind, and fuel-cell technologies to meet the region's electricity needs. Using the HOMER Pro software, various hybrid configurations were modeled, including photovoltaic (PV) panels, wind turbines, fuel cells, and battery storage. The study concluded that the grid-connected hybrid energy system, consisting of 600 kW of PV panels, 610 kW of wind turbines, and a 300 kW fuel cell, was the most efficient and cost-effective solution. This system was able to reliably meet the area's energy demands with a levelized cost of energy (LCOE) of $0.108/kWh, making it a viable option for sustainable energy production in similar remote locations.

Ahmed et al. [11] performed a techno-economic feasibility study on an off-grid hybrid renewable energy system for a rural village in Kech, Balochistan, Pakistan. The hybrid system, designed to meet the village's energy demands, combined solar PV modules, wind turbines, and battery backups. The system was modeled and optimized using the HOMER-Pro software, which identified the optimal configuration comprising 103 kW of solar PV, 12 kW of wind turbines, 224 lead-acid batteries, and a 29.1 kW converter. The study concluded that this configuration could effectively meet the village's daily energy requirement of 197.74 kWh with a peak load of 27.87 kW, achieving a cost of energy (COE) of $0.137/kWh. The research highlights the potential for implementing similar hybrid systems in remote areas of Pakistan to provide reliable and cost-effective electricity, addressing the challenges of grid extension in such regions. In the study by Ahsan and Iqbal [12], a hybrid solar power system was designed for an industrial unit in Lahore, Pakistan, using the HOMER Pro software. The system was configured to meet the electrical load demand of the industrial facility by integrating solar photovoltaic (PV) arrays with grid support and backup generators. The simulation results indicated that an 8382 kW solar PV array, combined with a 3119 kW inverter, could effectively reduce the cost of energy (COE) to $0.1020 per kWh, offering significant savings while ensuring reliable power supply. The study emphasized the potential of using solar energy to offset the reliance on conventional energy sources in industrial settings, reducing both operational costs and environmental impact. The findings suggest that such hybrid systems could play a vital role in enhancing energy security and sustainability in Pakistan's industrial sector. Rice et al. [13] modeled and optimized a hybrid photovoltaic (PV) and diesel generator system for off-grid applications in Lubumbashi, DR Congo, utilizing the HOMER Pro software. The research aimed to address the region's energy challenges by integrating solar PV with diesel generators and battery storage to provide a reliable and sustainable power solution. The study found that the hybrid system significantly reduced fuel consumption and operational costs, with a levelized cost of energy (LCOE) of $0.08857/kWh for the PV-battery system, compared to $0.109/kWh for the diesel hybrid PV-battery system. The optimized system not only ensured a stable power supply but also minimized carbon emissions, making it a cost-effective and environmentally friendly option for regions with unreliable grid access. This analysis highlights the potential for hybrid renewable energy systems to improve energy access and sustainability in remote and underserved areas. Muskan and Channi [14] evaluated the feasibility of a PV-diesel generator hybrid system for electricity generation in Akhnoor, Jammu and Kashmir, India, was examined using the HOMER software. The proposed system aimed to address the energy needs of a small town by optimizing the integration of solar photovoltaic (PV) arrays and a diesel generator. The analysis identified an optimal configuration consisting of 1.98 kW PV arrays and a 1.40 kW diesel generator, which resulted in a levelized cost of energy (LCOE) of $0.428/kWh and an overall net present cost (NPC) of $16,157. The study demonstrated that this hybrid system could provide a reliable and cost-effective energy solution, particularly in regions where grid connectivity is limited or unreliable. The research also highlighted the environmental benefits of the system, including reduced greenhouse gas emissions compared to conventional energy sources, making it a viable option for sustainable energy development in remote areas. Similar methodologies for hybrid renewable energy systems, integrating PV and wind technologies, have been successfully applied in off-grid settlements to ensure reliable power supply and environmental sustainability, as demonstrated by Tsiaras et al. [15]. As hybrid energy systems continue to evolve, integrating advanced technologies like green hydrogen storage can further enhance their sustainability and efficiency, as suggested by Lo Faro et al. [16].

The literature review reveals that renewable energy systems present a practical and cost-effective approach to meeting the energy demands of urban areas like Karachi. However, the adoption of these systems has been hindered by the high costs associated with off-grid systems, particularly those requiring large battery backups, as well as inconsistent government policies related to on-grid systems. This study aims to design and evaluate the feasibility of off-grid systems with limited battery storage, supplemented by a neighborhood diesel generator, to provide a more affordable and reliable energy solution for these areas.

3. Methodology

The methodology of this study focuses on evaluating the feasibility of an off-grid hybrid energy system specifically designed for the residential and commercial sectors in Karachi, Pakistan. The study involves selecting a site with seven houses, for which individual solar energy systems will be designed and installed, complemented by a shared neighborhood diesel generator integrated through an innovative distribution network and customized tariff model. Key factors such as solar insolation levels and the seasonal energy demands of these households are carefully considered to ensure the system's efficiency throughout the year. Meteorological data will be collected to accurately assess the solar potential at the chosen location, guiding the overall design and optimization of the system.

HOMER Pro software is utilized in this study due to its robust capability to model and optimize hybrid energy systems. The software allows for precise simulation of various system configurations by utilizing NASA's Satellite-derived Meteorological Data to accurately assess solar potential at the selected location. HOMER's ability to perform comprehensive techno-economic analysis, including calculations of the levelized cost of energy (LCOE) and net present cost (NPC), ensures that the system design is both cost-effective and reliable, making it an ideal tool for achieving the study's objectives.

3.1 *Site location*

The selected site for this study is an urban neighborhood in Karachi, precisely located at 24.919904 latitude and 67.145514 longitude. According to data from the HOMER Pro software, the region exhibits an average solar irradiance ranging from 5.45 to 5.6 kWh/m^2/day. The highest levels of solar irradiance are recorded in May, while the lowest occur in December. Figure 1 shows the site location, and Figure 2 illustrates the solar irradiance data, along with the clearness index for the selected location. As shown in Figure 1, none of the houses in the neighborhood currently have solar energy systems installed. All the houses in the selected neighborhood feature flat roofs, making them ideally suited for solar panel installations.

Figure 1. Selected site location

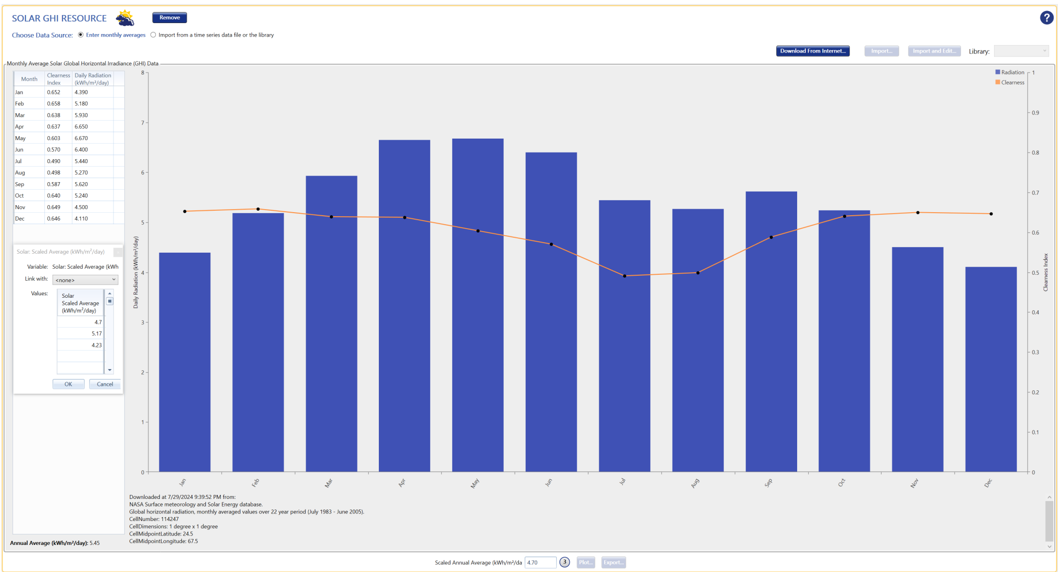


Figure 2. Monthly average irradiance levels and clearness index at Karachi

Each house within the selected neighborhood has a variable energy load, influenced by the differing number of occupants. House 1, situated at the center of the location, serves as the baseline with an energy requirement of 30 kWh/day. The electrical load distribution for House 1 is detailed in Figure 3, which indicates that the highest energy demand occurs during the summer months, from May to September, primarily due to the increased use of air conditioning systems. This peak in electricity consumption highlights the seasonal variability in energy requirements across the neighborhood.

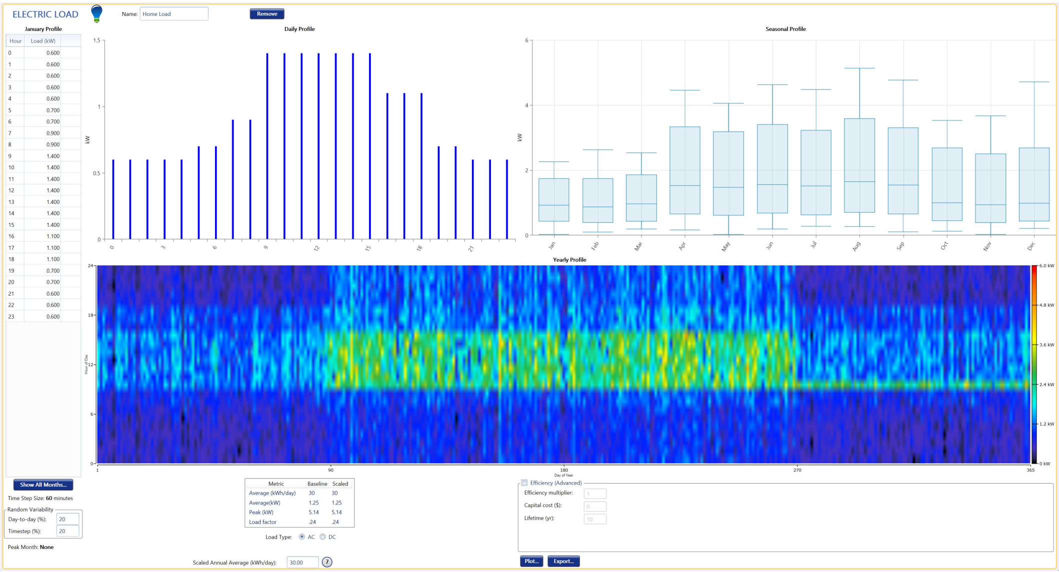


Figure 3. Electrical load details

3.2 *Solar resource*

Karachi, like other cities in Pakistan, benefits from extended periods of solar radiation, with daylight hours ranging between 10 to 12 h even during winter months. The region experiences its highest solar irradiance levels in May, while the lowest are recorded in December. According to data from the HOMER Pro software, the average solar irradiance for the site ranges from 5.45 to 5.6 kWh/m^2/day, as shown in Figure 2. The clearness index for the location varies between 0.49 and 0.658. Temperature-wise, the highest average temperature in summer is observed in June at 29.7 °C, while the lowest average temperature occurs in January at 19 °C. However, during peak summer months, daytime temperatures can reach as high as 40–45 °C, as illustrated in Figure 4.

3.3 *Load details*

The figure below illustrates the energy load distribution for the seven houses within the selected neighborhood. The primary loads in each house include air conditioning units, fans, LED lights, motors, TVs, and refrigerators. House 1, located at the center of the neighborhood, serves as the baseline with an energy demand of 30 kWh/day. The load distribution for the other houses is 15 kWh/day, 20 kWh/day, 25 kWh/day, 35 kWh/day, 40 kWh/day, and 45 kWh/day.

This variation in load is anticipated due to differences in the number of occupants per house and their respective usage patterns and lifestyles. All the houses have approximately the same area and share a similar method of construction, primarily using concrete. The electrical load distribution for House 1 is detailed in Figure 3, which shows that the highest energy demand occurs during the summer months, from May to September, primarily due to the increased use of air conditioning systems. Notably, daytime energy consumption is higher than nighttime usage, as non-essential activities—such as washing clothes, operating motor pumps, ironing, and cleaning—are scheduled during the day to maximize the use of solar energy and minimize battery storage requirements. The peak in electricity consumption in summer months underscores the seasonal variability in energy requirements across the neighborhood.

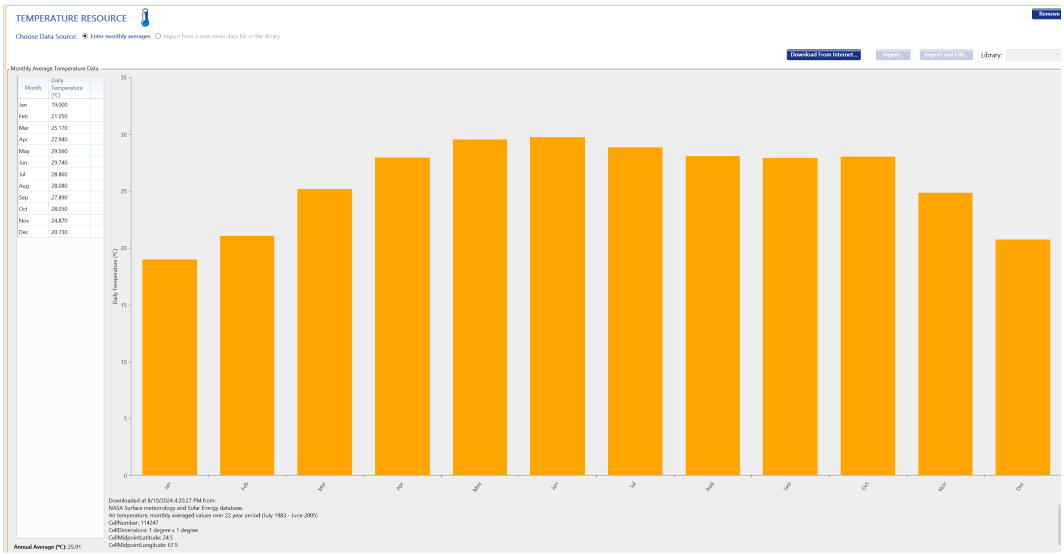


Figure 4. Site temperature profile

4. System description

For the techno-economic analysis and system design, accurate technical parameters and cost data for each component are essential. The HOMER Pro software (version 3.13.8) was employed to assess the system, enabling detailed modeling and optimization of the proposed hybrid energy system. The system's key components include photovoltaic (PV) panels, batteries, a converter, and a diesel generator. Cost and technical data for these components were collected from online datasheets, relevant literature, and market surveys. The objective is to design an off-grid solar energy system for each house, complemented by a shared diesel generator for backup. The diesel generator will be connected to the DC bus to charge the batteries as needed and will supply power to each house through a single-phase connection and breaker. Additionally, each house will be equipped with a separate meter to monitor electricity usage from the diesel generator. Figure 5 shows the system block diagram.

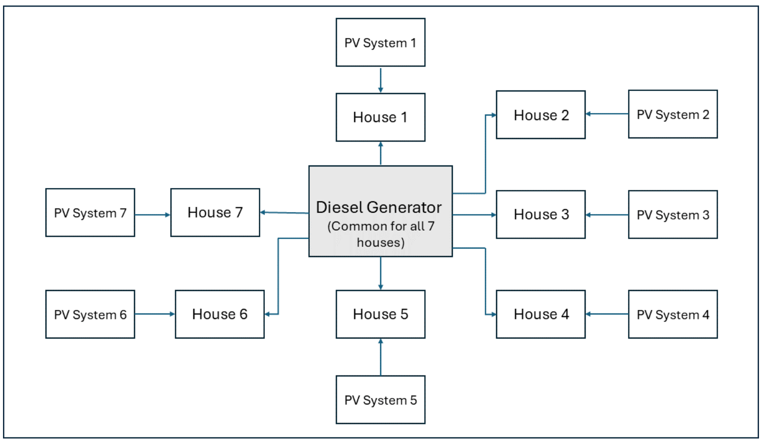


Figure 5. System block diagram

The schematic diagram of the system designed in HOMER Pro is as shown in Figure 6. The technical specifications of each major component used in the design are provided in the following sections.

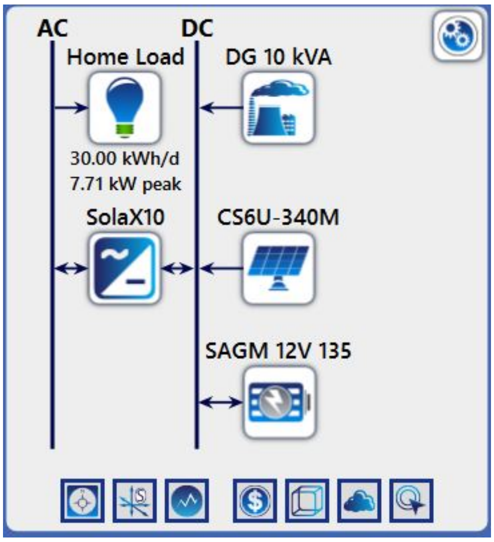


Figure 6. System model for each house

4.1 *PV panels*

In this study, the CS6U-340M solar photovoltaic (PV) module was selected. Each module has a capacity of 340 W and an efficiency of 17.49%, with an operating temperature range of −40 °C to +85 °C. Initial capital cost is $207 per kW, and replacement cost is $187 per kW. Operating and maintenance (O&M) expenses are $12 per kW annually, with an expected lifespan of 25 years. Technical specifications under standard test conditions (STC) are detailed in Table 1, and PV power output is shown in Figure 7.

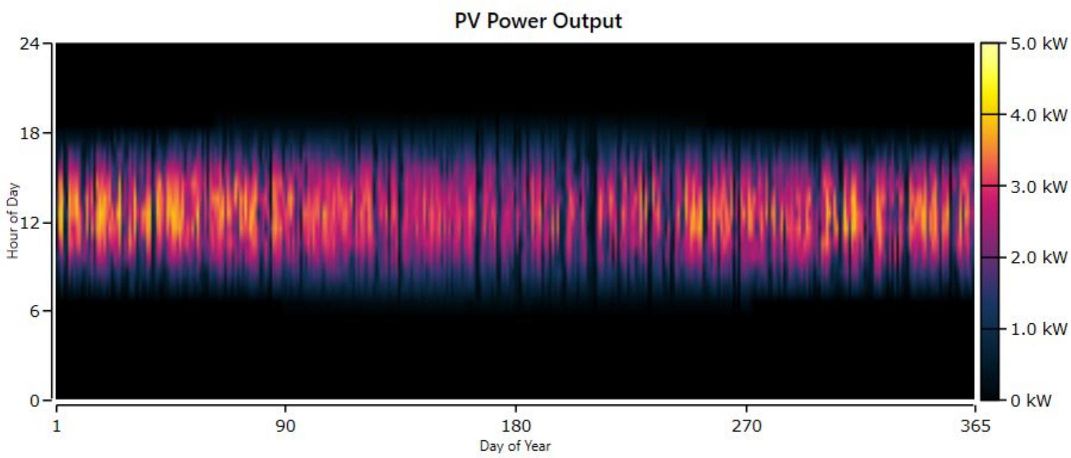


Figure 7. PV power output

Table 1. PV module specifications

Parameter	Values
Model	CS6U-340M
Manufacturer	Canadian Solar
Panel Type	Monocrystalline
Nominal Maximum Power (P_{max})	340 W
Operating Voltage (V_{mp})	37.8 V
Operating Current (I_{mp})	8.87 A
Operating Temperature	-40 °C ~ +85 °C
Cell Arrangement	72 cells (6 × 12)
Module Efficiency	17.49%
Junction box rating	IP 67
Weight	22.4 kg

4.2 *Batteries*

In this study, the AGM Deep Cycle Trojan SAGM 12 V 135 battery is utilized for energy storage. The battery has a nominal capacity of 1.68 kWh and a maximum capacity of 140 Ah, with a roundtrip efficiency of 85%. The initial capital cost is $370 per unit, with a replacement cost of $350. Annual operating and maintenance (O&M) expenses are $5 per year. The minimum state of charge (SOC) is set at 20%, with a lifespan of 12 years. Technical specifications are detailed in Table 2, and the SOC is illustrated in Figure 8.

Table 2. Battery specifications

Parameter	Values
Model	Trojan SAGM
Nominal Voltage	12 V
Nominal Capacity	1.68 kWh
Maximum Capacity	140 Ah
Roundtrip Efficiency	85%
Max. Charge Current	27 A
Max. Discharge Current	300 A
Bus Voltage	48 V
Cycles @50% DoD	1700 cycles
Annual Throughput	1460 kWh
Expected Life	12 Years

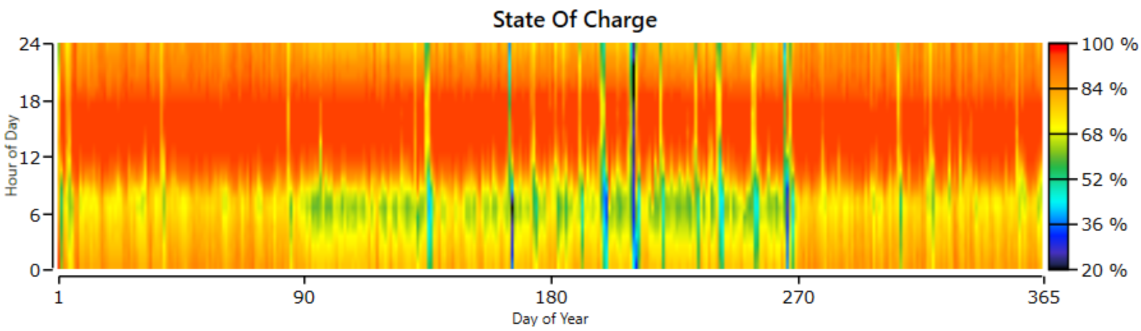


Figure 8. Battery state of charge

4.3 *Converter*

In this study, the Solax X3 Hybrid X10 converter is utilized for AC-DC and DC-AC conversion. The bidirectional converter has a capacity of 10 kW with an efficiency of 97.6%. The initial cost is $2000, and the replacement cost is $2100. The converter has a lifespan of 15 years and is designed to manage energy flow between the DC and AC components of the system, ensuring efficient power conversion and integration. Table 3 shows more details.

Table 3. Converter specifications

Parameter	Values
Maximum Power	10 kW
Max AC Output Current	16.1 A
Frequency	50 Hz or 60 Hz
Efficiency	97%
MPPT Voltage Range	180 ~ 950 V
No. of MPPT trackers	2
Strings per MPPT tracker	2/1
THD (rated power)	<3
Expected Life	15 Years

4.4 *Diesel generator*

Table 4 provides details of the selected diesel generator. Table 5 displays the fuel consumption details, while Table 6 outlines the associated emissions. The diesel generator is connected to the DC bus through charge controllers, with a built-in rectifier in the selected inverter converting the AC power from the generator to DC. The generator charges the batteries for use during nighttime or on rainy and cloudy days, as the system is entirely off-grid, thereby reducing the need for a large battery bank. The output power limit from diesel generator for each house has been set to 2 kW.

Table 4. Diesel generator specifications

Parameter	Values
Fuel Type	Diesel
Minimum Load Ratio	25%
Life of operation	12 Years
Capacity Factor	1.9%
Governor Type	Mechanical
Engine Compression Ratio	23:1
Displacement	1.1 litre
Mean Electrical Efficiency	32.9%

Table 5. Diesel fuel consumption

Parameter	Values
Net fuel consumption	81.6 L
Fuel consumption per day (avg)	0.22 L
Specific fuel consumption	0.309 L/kWh
Fuel curve intercept	0.5 L/hr
Fuel curve slope	0.273 L/hr/kW
Lower heating value	43.2 MJ/kg
Density	820 kg/m^3

Table 6. Expected emissions

Parameter	Values
Carbon Monoxide	16.34 g/L
Unburned Hydrocarbons	0.72 g/L
Particulate matter	0.098 g/L
Fuel sulfur converted to PTM	2.2%
Nitrogen Oxides	15.359 g/L

5. Optimization and simulation results

The simulation software HOMER-Pro runs thousands of simulations to get the most feasible and optimum design system

5.1 *System design*

In our design, there are seven houses, each with its own off-grid solar energy system tailored to meet the specific energy demands, which range from 15 kWh/day to 45 kWh/day, depending on the number of occupants and their living style. For the house with a 15 kWh/day load, the system includes 7.61 kW of PV panels and 12 batteries. The house with a 20 kWh/day load is equipped with 8.72 kW of PV panels and 12 batteries. For a 25 kWh/day load, the system comprises 15.0 kW of PV panels and 16 batteries. The house with a 30 kWh/day load uses 18.3 kW of PV panels and 16 batteries, while the house with a 35 kWh/day load is designed with 19.1 kW of PV panels and 20 batteries. For a 40 kWh/day load, the system includes 28.8 kW of PV panels and 24 batteries, and for the highest load of 45 kWh/day, the system is configured with 29.3 kW of PV panels and 20 batteries. Additionally, the generator output is limited to 2 kW for each house, as this generator is shared by all seven houses to charge the batteries when needed. The detailed configurations and system components are illustrated in Figure 9.

Sensitivity		Architecture				Cost				DG 10kVA					SAGM 12V 135	
Home Load Scaled Average (kWh/d)	Solar Scaled Average (kWh/m²/day)	CS6U-340M (kW)	DG 10kVA (kW)	SAGM 12V 135 (#)	Dispatch	NPC ($)	LCOE ($/kWh)	Operating cost ($/yr)	CAPEX ($)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)	Autonomy (hr)	Annual Throughput (kWh/yr)
15.0	4.23	11.6	2.00	8	CC	$15,488	$0.300	$598.35	$7,752	27.0	35.5	11.5	21.6	21.3	17.2	2,031
15.0	4.70	7.61	2.00	12	CC	$15,563	$0.296	$553.54	$8,407	48.0	68.5	21.9	38.4	40.7	25.8	2,115
15.0	5.17	7.41	2.00	8	CC	$14,807	$0.287	$612.86	$6,884	66.0	92.5	29.6	52.8	55.1	17.2	2,078
20.0	4.23	12.3	2.00	12	CC	$20,263	$0.294	$813.90	$9,742	78.0	87.0	28.9	62.4	53.7	19.3	2,752
20.0	4.70	8.72	2.00	12	CC	$20,438	$0.298	$886.94	$8,972	154	183	60.1	123	112	19.3	2,778
20.0	5.17	9.02	2.00	12	CC	$19,637	$0.288	$820.93	$9,025	113	129	42.8	90.4	79.5	19.3	2,760
25.0	4.23	16.7	2.00	12	CC	$25,444	$0.282	$1,102	$11,198	99.0	136	43.6	79.2	81.1	15.5	3,507
25.0	4.70	15.0	2.00	16	CC	$24,792	$0.276	$967.47	$12,285	54.0	67.0	21.8	43.2	40.6	20.6	3,531
25.0	5.17	14.1	2.00	16	CC	$24,500	$0.271	$958.34	$12,111	56.0	66.1	21.8	44.8	40.5	20.6	3,548
30.0	4.23	16.6	2.00	20	CC	$28,952	$0.283	$1,138	$14,242	77.0	94.1	30.8	61.6	57.3	21.5	4,155
30.0	4.70	18.3	2.00	16	CC	$28,392	$0.275	$1,176	$13,185	65.0	82.0	26.7	52.0	49.6	17.2	4,127
30.0	5.17	18.3	2.00	16	CC	$28,005	$0.274	$1,150	$13,140	57.0	67.0	22.1	45.6	41.0	17.2	4,082
35.0	4.23	18.4	2.00	20	CC	$33,940	$0.283	$1,463	$15,032	157	204	66.0	126	123	18.4	4,867
35.0	4.70	19.1	2.00	20	CC	$32,653	$0.272	$1,353	$15,165	86.0	115	37.1	68.8	69.1	18.4	4,839
35.0	5.17	18.5	2.00	20	CC	$32,115	$0.269	$1,322	$15,020	83.0	98.6	32.4	66.4	60.3	18.4	4,800
40.0	4.23	29.5	2.00	20	CC	$38,983	$0.285	$1,648	$17,678	86.0	115	37.2	68.8	69.1	16.1	5,420
40.0	4.70	28.8	2.00	24	CC	$39,278	$0.286	$1,567	$19,015	72.0	84.8	27.9	57.6	51.9	19.3	5,419
40.0	5.17	17.9	2.00	20	CC	$37,690	$0.272	$1,727	$15,366	224	286	92.8	179	173	16.1	5,561
45.0	4.23	35.2	2.00	20	CC	$43,841	$0.285	$1,902	$19,251	106	118	39.2	84.8	72.9	14.3	6,047
45.0	4.70	29.3	2.00	20	CC	$42,761	$0.278	$1,913	$18,037	158	187	61.5	126	114	14.3	6,105
45.0	5.17	29.6	2.00	20	CC	$41,840	$0.273	$1,839	$18,068	112	130	42.8	89.6	79.5	14.3	6,087

Figure 9. System design for each house

Sensitivity analysis was conducted to assess the system's response to fluctuations in solar irradiance, reflecting natural variability from weather patterns or seasonal changes, such as rainy or cloudy days. Figure 9 illustrates how component requirements adjust when a ±10% variation in solar irradiance is applied as a sensitivity input.

The dispatch strategy significantly influences the operation of the diesel generator in a hybrid PV-diesel-battery system, impacting fuel consumption and emissions. In this model, the Cycle Charging (CC) strategy was chosen for its efficiency, as it operates the generator at a higher load factor, ensuring the battery is charged during operation. This approach reduces generator idle time, extends system autonomy during low solar irradiance periods, and minimizes the need for frequent generator start-ups, making it more economical and environmentally friendly compared to Load Following (LF) [17].

5.2 *Electrical output*

Figure 10 presents the optimized results for House 1, which has a daily load of 15 kWh. The HOMER optimization identified the most efficient configuration as 7.61 kW of PV panels combined with three strings of Trojan SAGM 12 V 135 Ah batteries. The PV array consists of 340 W flat-plate CS6U-340M Canadian Solar panels. To match the 48 V DC bus configuration, each string contains four batteries connected in series, totaling 12 batteries for the system. The PV panels are expected to generate 9017 kWh/year, with 98.3% of the energy sourced directly from solar power. The diesel generator, limited to a 2 kW output, serves as a backup and is integrated with a cycle charging dispatch strategy to ensure the batteries are charged whenever excess energy is generated. This strategy was chosen over the load-following dispatch strategy, which only serves the immediate load and does not prioritize battery charging. The system's autonomy is calculated at 25.8 h, indicating that during periods of low solar availability, such as rainy days, the batteries can sustain the house's power needs for more than a full day. The monthly electrical production analysis indicates peak PV generation during March, April, and May, with the lowest production in July, coinciding with the monsoon season in Pakistan.

Figure 10. Electrical characterstics

Figure 11 presents an exhaustive time series analysis of the PV power output and battery state of charge over a one-year period. The graph reveals that the battery state of charge experiences sharp declines from 80% to 30–35% during the months of June, July, and September, corresponding with lower solar irradiance levels due to rainy or cloudy days. The solar output varies throughout the year with changing irradiance levels, reflecting the natural variability of renewable energy generation and its influence on battery charge levels.

Figure 11. Time series analysis

5.3 *Economic analysis*

The Net Present Cost (NPC) is a critical economic metric used to assess the total lifetime cost of a system, including initial investment, operational, maintenance, and replacement expenses throughout the project's duration. By discounting future costs to their present value, the NPC accounts for the time value of money, making it a crucial factor in determining the long-term financial viability of energy systems. The configuration with the lowest NPC typically offers the most cost-effective solution, minimizing overall expenses over the system's operational lifespan.

At time t = 0, the NPC is determined by summing the present values of all project-related costs, as outlined in Equation (1) [18]. The Discount Factor (DF), used to convert future costs into present values, and the Salvage Value (SV), which represents the residual value of components at the end of the system's operational life, are both calculated as outlined in Equations (2) and (3) [19].

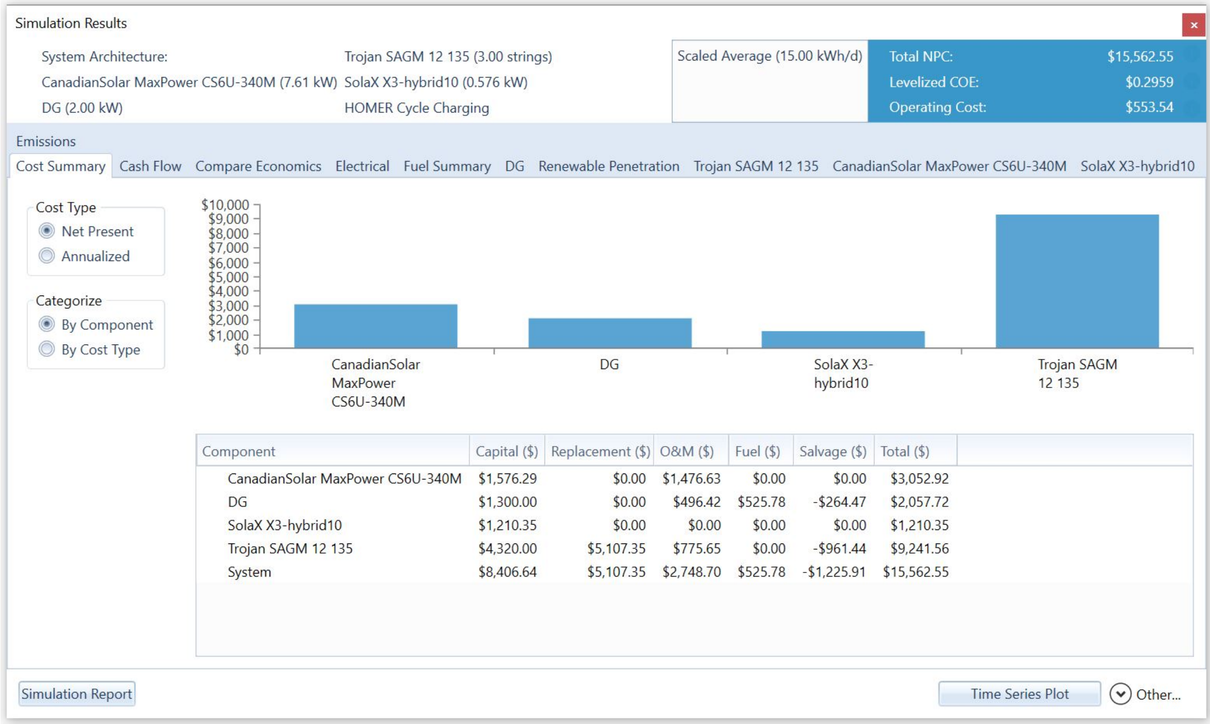
$$NPC = I_0 + \sum_{t=0}^{T} I_t \times DF - SV \times DF \tag{1}$$

$$DF = \left(1 + \frac{i}{100}\right)^{-t} \tag{2}$$

$$SV = C_{rep} \times \frac{R_{rem}}{R_{comp}} \tag{3}$$

where I_0 represents the initial investment cost at t = 0, I_t is the cost during time period t, T is the project lifetime in years, and i is the discount rate. Furthermore, the parameters C_{rep}, R_{rem}, R_{comp} refer to the component replacement cost, remaining life, and total component lifetime, respectively. These elements ensure a comprehensive and precise calculation of the NPC, allowing for a more accurate comparison between different system configurations

Figure 12 presents the comprehensive cost analysis for the system. The total Net Present Cost (NPC) is calculated at $15,562.55, covering all expenses related to equipment installation, operation, and maintenance over the system's 25-year lifespan. The Levelized Cost of Energy (LCOE) is determined to be $0.2959, reflecting the net present cost of electricity generation over the system's lifetime. The annual operating cost is estimated at $553.54, with battery replacements scheduled for the 9th and 17th years, each requiring an investment of $4080. By the end of the 25-year period, a salvage value of $5117.39 is anticipated. The component-level costs, including those for batteries, solar PV, and other system components, are detailed in Figure 12, highlighting their respective contributions to the overall investment, while Figure 13 depicts the cash flow graph for the system.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
CanadianSolar MaxPower CS6U-340M	$1,576.29	$0.00	$1,476.63	$0.00	$0.00	$3,052.92
DG	$1,300.00	$0.00	$496.42	$525.78	-$264.47	$2,057.72
SolaX X3-hybrid10	$1,210.35	$0.00	$0.00	$0.00	$0.00	$1,210.35
Trojan SAGM 12 135	$4,320.00	$5,107.35	$775.65	$0.00	-$961.44	$9,241.56
System	$8,406.64	$5,107.35	$2,748.70	$525.78	-$1,225.91	$15,562.55

Figure 12. Cost summary for each house

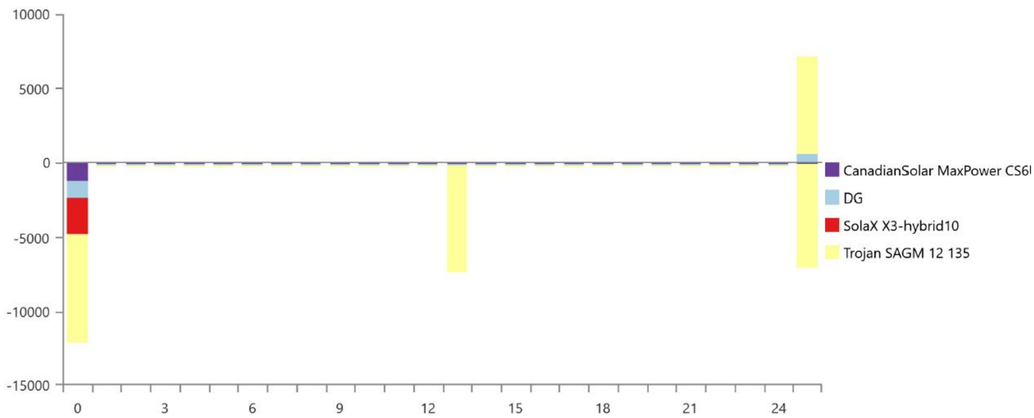


Figure 13. Cash flow

6. Conclusions

The study focused on designing a solar energy solution integrated with a shared diesel generator for a small neighborhood comprising 7 closely located houses. The concept of a shared diesel generator was adopted to reduce individual maintenance and troubleshooting costs, as well as to alleviate the capital cost burden on each household. In this shared arrangement, the diesel generator operates at a normal load, ensuring it does not run below 30% of its capacity, which enhances its efficiency and extends its operational lifespan.

Each house is equipped with its own off-grid solar system, while the diesel generator, installed and maintained by a local supplier, serves as a common backup power source. A key advantage of this approach is the use of individual distributed PV systems for each house, which is cost-effective due to the shorter distances between the solar panels and each house's load. The diesel generator setup is also streamlined, as all seven houses are located closely enough to be connected by a single wire with a breaker and meter for each house. This centralized generator network, scalable for future expansion, will be operated by a third-party contractor responsible for its management and scheduled maintenance.

The decision to utilize solar energy was driven by the abundant solar resource available in Karachi, with an average of 4.11 kWh/m^2/day in December and a peak of 6.67 kWh/m^2/day in May. This system presents a viable opportunity for entrepreneurs to offer an efficient and cost-effective energy solution to urban neighborhoods, reducing dependency on utility companies and alleviating the burden of high government taxes. The optimized battery bank design and shared generator system reduce the overall cost of installation, operation, and maintenance compared to standalone systems with large battery backups or individual generators. Consumers are billed based on their actual usage, monitored through individual meters, making this system more economical and easier to manage. Overall, the proposed system design offers a reliable, cost-effective, and efficient solution to meet the energy needs of residential and small business sectors in urban areas of Karachi and throughout Pakistan.

Conflict of interest

The authors declare no potential conflict of interest with respect to the research, authorship, or publication of this article.

References

[1] "Global Energy Review 2021—Analysis," IEA. Accessed: Aug. 8, 2024. [Online]. Available: https://www.iea.org/reports/global-energy-review-2021

[2] H. Qudrat-Ullah, "A review and analysis of renewable energy policies and CO_2 emissions of Pakistan," *Energy*, vol. 238, p. 121849, Jan. 2022, https://doi.org/10.1016/j.energy.2021.121849.

[3] M. A. Raza, K. L. Khatri, A. Israr, M. I. U. Haque, M. Ahmed, K. Rafique, et al., "Energy demand and production forecasting in Pakistan," *Energy Strat. Rev.*, vol. 39, p. 100788, Jan. 2022, https://doi.org/10.1016/j.esr.2021.100788.

[4] "Pakistan further removes fuel subsidies to win IMF funding -finmin | Reuters." Accessed: Aug. 8, 2024. [Online]. Available: https://www.reuters.com/markets/asia/pakistan-further-removes-fuel-subsidies-win-imf-funding-finmin-2022-06-15/.

[5] "Karachiites, forget relief and get ready for another tax in KE bills—Pakistan—DAWN.COM." Accessed: Aug. 8, 2024. [Online]. Available: https://www.dawn.com/news/1849701

[6] "IPPs: The Real Issues," Pakistan Institute of Development Economics. Accessed: Aug. 8, 2024. [Online]. Available: https://pide.org.pk/research/ipps-the-real-issues/

[7] M. T. Naqash, "Assessment of Renewable Energy Potential in a Region Based on Climatic Conditions," *Int. J. Energy Environ. Econ.*, vol. 30, no. 1, pp. 83–95, 2022.

[8] W. ur Rehman, I. A. Sajjad, T. N. Malik, L. Martirano, and M. Manganelli, "Economic analysis of net metering regulations for residential consumers in Pakistan," in *Proc. 2017 IEEE Int. Conf. Environ. Electr. Eng. 2017 IEEE Ind. Commer. Power Syst. Europe*, Milan, Italy, Jun. 6–9, 2017, pp. 1–6, https://doi.org/10.1109/EEEIC.2017.7977733.

[9] "A solar power policy crisis for Pakistan—Asia Times." Accessed: Aug. 9, 2024. [Online]. Available: https://asiatimes.com/2024/05/a-solar-power-policy-crisis-for-pakistan/.

[10] M. U. Manoo, F. Shaikh, L. Kumar, and S. I. Mustapa, "Comparative Investigation of On-Grid and Off-Grid Hybrid Energy System for a Remote Area in District Jamshoro of Sindh, Pakistan," *Urban Sci.*, vol. 7, no. 2, p. 2, Jun. 2023, https://doi.org/10.3390/urbansci7020063.

[11] A. Ali, "Techno-economic Feasibility Analysis of an Off-grid Hybrid Renewable Energy System for Rural Electrification," *J. Electr. Electron. Eng.*, vol. 9, p. 7, Feb. 2021, https://doi.org/10.11648/j.jeee.20210901.12.

[12] L. Ahsan and M. T. Iqbal, “Design of Hybrid Electrical Power System for an Industrial Unit in Pakistan,” Accessed: Aug. 9, 2024. [Online]. Available: https://www.academia.edu/download/74843527/NECEC2021_3.pdf

[13] I. K. Rice, H. Zhu, C. Zhang, and A. R. Tapa, “A Hybrid Photovoltaic/Diesel System for Off-Grid Applications in Lubumbashi, DR Congo: A HOMER Pro Modeling and Optimization Study,” *Sustainability*, vol. 15, no. 10, p. 10, Jan. 2023, https://doi.org/10.3390/su15108162.

[14] H. K. Channi, “Optimal designing of PV-diesel generator-based system using HOMER software,” *Mater. Today: Proc.*, 2023, https://doi.org/10.1016/j.matpr.2023.01.053.

[15] E. Tsiaras, D. N. Papadopoulos, C. N. Antonopoulos, V. G. Papadakis, and F. A. Coutelieris, “Planning and assessment of an off-grid power supply system for small settlements,” *Renew. Energy*, vol. 149, pp. 1271–1281, Apr. 2020, https://doi.org/10.1016/j.renene.2019.10.118.

[16] M. Lo Faro, D. A. Cantane, and F. Naro, “In the path for creating Research-to-business new opportunities on green hydrogen between Italy and Brazil,” *Int. J. Hydrog. Energy*, vol. 48, no. 32, pp. 11876–11884, Apr. 2023, https://doi.org/10.1016/j.ijhydene.2022.05.089.

[17] M. A. Omar, “Green mechanism: Opportunities for corporate investment in PV/battery/diesel hybrid systems with techno-economic and environmental analysis, *Energy Explor. Exploitation*, p. 01445987241269009, Aug. 2024, https://doi.org/10.1177/01445987241269009.

[18] M. A. Omar, “The Significance of Considering Battery Service-Lifetime for Correctly Sizing Hybrid PV—Diesel Energy Systems,” *Energies*, vol. 17, no. 1, p. 1, Jan. 2024, https://doi.org/10.3390/en17010103.

[19] M. A. Omar and M. M. Mahmoud, “Grid connected PV-home systems in Palestine: A review on technical performance, effects and economic feasibility,” *Renew. Sustain. Energy Rev.*, vol. 82, pp. 2490–2497, Feb. 2018, https://doi.org/10.1016/j.rser.2017.09.008.