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Comprehensive Techno-Economic and Environmental Comparison with Sensitivity Analysis of Optimized Hybrid Energy Systems for Residential Prosumers

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Abstract

With increasing residential electricity demand, hybrid energy systems capable of simultaneously improving affordability, reliability, and environmental performance have become increasingly important. This paper develops an integrated techno-economic and environmental assessment framework for grid-connected residential energy systems under unreliable grid conditions and applies it to a real-world residential case study in Fayoum, Egypt. In the proposed framework, the utility grid is treated as the primary electricity source, while PV, diesel generation, and battery storage are evaluated as backup/support options. Six grid-connected hybrid configurations, namely Grid/Diesel, Grid/PV/Diesel, Grid/PV/Diesel/Battery, Grid/Diesel/Battery, Grid/PV/Battery, and Grid/Battery, were evaluated under identical load, solar resource, and economic conditions to identify the minimum net present cost (NPC)configuration capable of satisfying a specified service level, expressed in terms of the maximum allowable unmet load ratio. The optimization problem was formulated as a single-objective model that minimizes NPC, subject to technical constraints and a service level constraint represented by a zero unmet load requirement in this study. Additional indicators, including levelized cost of energy (LCOE), renewable fraction, CO_2 emissions, and electricity purchased from the grid, were used for comparative performance evaluation. The candidate systems were simulated and optimized under frequent grid outage conditions using HOMER Pro. The results identify the Grid/PV/Battery configuration as the preferred base case backup/support configuration among the evaluated alternatives, achieving the lowest NPC of USD 8949, the lowest LCOE of USD 0.135/kWh, the highest renewable fraction of 55.1%, and the lowest annual CO_2 emissions of 2333 kg/yr, while satisfying the zero unmet load requirement. Compared with the base Grid/Diesel system, the optimal configuration reduces annual operating cost from USD 1204/yr to USD 648.19/yr and lowers emissions by approximately 50%, despite requiring a higher initial capital investment. Sensitivity analysis shows that the preferred solution remains robust across most of the examined financing parameter space. The PV derating factor analysis further indicates that the Grid/PV/Battery configuration remains optimal at higher PV derating levels of 70–80%, whereas the preferred solution shifts toward Grid/Diesel at lower derating levels of 50–60%. Overall, the results demonstrate that combining service-level-constrained NPC minimization with comparative techno-economic and environmental evaluation provides a robust basis for identifying suitable backup-supported grid-connected residential energy solutions under unreliable grid conditions.

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Keywords: hybrid energy systems; residential prosumers; techno-economic-environmental assessment; PV/Battery systems; grid outage; sensitivity analysis

1. Introduction

Frequent power outages have become increasingly prevalent in many developing countries, including Egypt [1–3]. These outages disrupt daily life and have significant economic and social implications, particularly for sectors that depend on a continuous electricity supply, such as healthcare, education, residential services, and industry. Recently, the situation has been further aggravated by global economic instability and energy market disruptions [4], which have contributed to rising fuel prices, supply chain constraints, and additional pressure on already strained national economies. Egypt, in particular, continues to rely heavily on fossil fuel-based energy sources to meet its electricity demand. The distribution of electricity generation by source in Egypt in 2023 shows that thermal sources accounted for 88% of total electricity generation [5]. This heavy dependence on fossil fuel-based generation raises important concerns regarding energy security, sustainability, and environmental impacts. Hydropower contributed 7% of electricity generation, reflecting its limited but stable role in the national energy mix, while new and renewable energy sources accounted for only 5% [5]. This relatively low share of clean energy highlights the need for increased investment, supportive policy measures, and accelerated deployment of renewable energy technologies. These conditions underscore the importance of developing more resilient, diversified, and adaptive power systems capable of withstanding both domestic pressures and global energy market disruptions.

Hybrid Renewable Energy Systems (HRESs) have become an important area of research and application in the transition toward low-carbon electricity systems because they integrate renewable generation, storage, conventional backup, and grid interaction within a unified operational framework. Early studies established the techno-economic value of hybrid systems for electrification and energy cost reduction, particularly in off-grid and weak-grid settings. For example, Akikur et al. [6] provided an early review of standalone and hybrid solar systems for rural electrification, while Ismail et al. [7] demonstrated the feasibility of PV–diesel hybrid systems for remote residential supply. Amutha and Rajini [8] further showed that HOMER-based evaluation can effectively compare alternative rural electrification solutions from both cost and technical perspectives. More recent work has expanded this field by examining advanced sizing approaches, wider technology combinations, and integrated optimization frameworks. Rezaei et al. [9] addressed hybrid energy system design from a combined exergy and economic perspective, whereas Medghalchi and Taylan [10] proposed a hybrid optimization framework for renewable systems with storage and hydrogen-based components. He et al. [11] also highlighted, through a recent review, that sizing optimization remains a central challenge in HRES design. Taken together, these studies show that careful system design is essential for balancing cost, reliability, and environmental performance.

Within this wider research context, the residential sector has received increasing attention, as households require electricity systems that are affordable, reliable, flexible, and environmentally sustainable. Nafeh et al. [12], for instance, showed the economic relevance of PV/Battery integration in grid-connected applications, while Brown et al. [13] emphasized the growing importance of rooftop solar deployment for households. At the same time, the economic performance of residential PV systems remains highly sensitive to pricing and compensation structures. Cai et al. [14] demonstrated that tariff design and demand response strongly affect the economics of residential rooftop PV integration,

and Brodnicke et al. [15] showed that export limits and grid emission assumptions can significantly change both environmental and cost outcomes. These findings indicate that the design of residential hybrid systems is strongly context-dependent and should be assessed under realistic local tariff and operational conditions.

A second important area of the literature examines the design and operation of hybrid energy systems under grid instability and outage-prone conditions. Jeyaraj et al. [16] reviewed the role of hybrid renewable systems in improving system stability, while Bansal [17] and Firoozi et al. [18] highlighted the importance of accurate system sizing and performance assessment in renewable-based hybrid applications. In residential and building-scale settings, Hyvönen et al. [19] examined storage feasibility for PV electricity in detached houses, Litjens et al. [20] analyzed the environmental benefits of combining PV and storage in buildings, and Zaidi et al. [21] studied grid-connected microgrid design for residential and commercial applications. Under outage-prone conditions, Tsianikas et al. [22] showed that PV/Battery systems can enhance grid outage resilience, while Wei et al. [23] demonstrated the techno-economic value of combining backup sources with storage in solar hybrid systems. Overall, these studies show that HRESs can improve reliability and reduce emissions, while also highlighting that the preferred system configuration is highly dependent on the local operating context.

Although significant progress has been made, several important gaps remain in the literature. First, many previous studies focus on off-grid systems or a single proposed configuration, which limits the ability to identify the most suitable design across a broader feasible solution space. This is evident in studies such as Ghafoor and Munir [24], Kolhe et al. [25], Olatomiwa et al. [26], Haghighat Mamaghani et al. [27], and Olatomiwa et al. [28], all of which addressed specific hybrid configurations in off-grid or certain applications. Second, a substantial portion of the literature emphasizes either techno-economic performance or component level analysis, while fewer studies integrate reliability, lifecycle cost, renewable contribution, and environmental performance within a single unified framework for residential applications. Examples include He et al. [29], Chauhan et al. [30], Li et al. [31], Ma et al. [32], Yao et al. [33], and Akbas et al. [34], which, although valuable, do not collectively provide a broad comparative residential framework under consistent assumptions. Third, although some studies consider grid connection, storage, and uncertainty, limited attention has been given to the combined influence of frequent grid interruptions, electricity purchasing tariffs, grid sell-back arrangements, and macro-financial conditions such as nominal discount rate, inflation, and diesel fuel price uncertainty on residential hybrid system selection. For instance, Das et al. [35] assessed standalone and grid-connected hybrid systems, Borerwe and Longe [36] examined battery storage economics, and Adewuyi and Aki [37] addressed renewable integration under uncertainty, but these studies do not explicitly combine the full set of assumptions considered in the present work.

Although several previous studies are closely related to the present manuscript, the current study differs from them in several important respects, including system scope, application context, reliability assumptions, and sensitivity analysis design. Van der Stelt et al. [38] analyzed household and community energy storage for residential prosumers with smart appliances using an MILP-based scheduling framework and dynamic pricing, with emphasis on storage feasibility and self-consumption rather than outage-driven hybrid architecture comparison. Nesamalar et al. [39] examined both on-grid and off-grid hybrid energy systems for an educational institution using HOMER, focusing on dispatch strategies and sensitivity to fuel price and solar radiation rather than residential prosumer operation under frequent outages. Alayi et al. [40] investigated a multi-source system for an urban community in Iran, but their study focused on a different technology mix and sensitivity structure. In contrast, the present study develops an integrated comparative

framework for six grid-connected residential hybrid system configurations under identical load, tariff, outage, and financial assumptions. Unlike earlier work that typically examines a single architecture, a narrower technology set, or a more limited performance scope, the present study evaluates the candidate systems simultaneously in terms of NPC, LCOE, renewable fraction, operational CO_2 emissions, grid dependence, and full reliability.

Motivated by this gap, the present study applies the proposed framework to a real-world residential case study in Fayoum, Egypt, a setting characterized by favorable solar resources together with practical concerns related to grid reliability, electricity cost, and long-term investment conditions. Six grid-connected configurations are modeled and compared, including combinations of grid supply, PV generation, diesel backup, and battery storage. In addition to the comparative system assessment, the analysis incorporates sensitivity analysis of the principal financial assumptions, namely the nominal discount rate, inflation rate, and diesel fuel price, and examines the trade off between capital investment and operating cost across the feasible solution space. The study further extends the sensitivity assessment by evaluating the effect of the PV derating factor over the range of 50–80%, in order to examine how assumptions regarding effective PV performance influence system selection and long-term economic outcomes.

The present study makes two main contributions. First, it develops a unified comparative framework for evaluating six grid-connected residential hybrid energy system configurations under a consistent set of technical, tariff, outage, and financial assumptions. Unlike many previous studies that focus on a single architecture, off-grid operation, or a narrower set of evaluation criteria, this study compares candidate systems simultaneously in terms of NPC, LCOE, renewable fraction, operational CO_2 emissions, grid dependence, and zero unmet load. Second, it extends the literature by explicitly examining how financial conditions, particularly the nominal discount rate, inflation rate, and diesel fuel price, together with PV derating level, influence the relative attractiveness of alternative residential hybrid configurations. In this way, the study provides not only a case-specific assessment for Fayoum, Egypt, but also a methodological basis for identifying cost-effective, reliable, and environmentally preferable residential hybrid systems in regions characterized by strong solar potential, tariff variability, financing constraints, and imperfect grid reliability.

To position the contribution of the present work more clearly, Table 1 compares several representative studies with the current manuscript in terms of application context, methodological focus, evaluation dimensions, and remaining limitations.

Table 1. Comparison of representative previous studies with the present work.

Study	Main Application Context	System Scope/ Methodological Focus	Main Evaluation Dimensions	Main Limitation Relative to the Present Study	Distinct Contribution of the Present Study
van der Stelt et al. [38]	Residential prosumers with smart appliances; household and community storage	MILP-based scheduling of storage for self consumption and cost management under dynamic pricing	Economic feasibility, storage operation, self consumption	Focuses primarily on storage scheduling rather than comparative hybrid system architecture assessment; does not address outage driven reliability using PV/Battery/Diesel alternatives	Evaluates six grid-connected hybrid configurations under identical technical, tariff, outage, and financial assumptions, with explicit reliability-oriented comparison

Table 1. *Cont.*

Study	Main Application Context	System Scope/ Methodological Focus	Main Evaluation Dimensions	Main Limitation Relative to the Present Study	Distinct Contribution of the Present Study
Nesamalar et al. [39]	Educational institution; on-grid and off-grid hybrid system design	HOMER-based techno economic analysis with sensitivity to fuel price and solar radiation	Cost, energy supply feasibility, dispatch strategy comparison	Application context is institutional rather than residential; does not focus on prosumer operation, time-of-use tariffs, or frequent outage conditions in household systems	Examines a residential prosumer case and incorporates grid outages, tariff structure, sell-back arrangements, and macro-financial sensitivity
Alayi et al. [40]	Urban community case study in Iran	Multi source hybrid system with sensitivity analysis	Techno-economic evaluation and sensitivity to resource conditions	Different technology mix and system context; limited emphasis on-grid-connected residential PV/Battery/Diesel comparison and outage constrained reliability	Provides a targeted comparative framework for residential hybrid architectures with explicit treatment of grid dependence and full reliability
Das et al. [35]	Standalone and grid-connected hybrid energy systems	Comparative techno-economic feasibility of hybrid configurations	Feasibility, economics, general performance	Broader hybrid system comparison, but without the present study's emphasis on residential outage conditions, tariff asymmetry, and financial environment sensitivity	Adds a case-specific yet methodologically transferable framework for residential systems under realistic outage and tariff conditions
Borerwe and Longe [36]	Stationary battery storage applications	Large-scale battery storage techno-economic analysis	Storage economics	Focuses on storage economics in isolation rather than integrated household hybrid system design	Embeds battery storage within a whole system residential comparison that also includes PV, diesel backup, and grid interaction
Adewuyi and Aki [37]	Renewable energy planning under uncertainty	Planning model with demand response and uncertainty considerations	Flexibility, uncertainty, operational performance	Addresses broader planning issues, but not configuration level comparison of residential hybrid systems under unified assumptions	Concentrates on configuration selection for residential hybrid systems while also considering financial sensitivity

Table 1. *Cont.*

Study	Main Application Context	System Scope/ Methodological Focus	Main Evaluation Dimensions	Main Limitation Relative to the Present Study	Distinct Contribution of the Present Study
Present study	Residential prosumer system in Fayoum, Egypt	Integrated comparative framework for six grid-connected configurations: Grid/Diesel, Grid/PV/Diesel, Grid/PV/Diesel/Battery, Grid/Diesel/Battery, Grid/PV/Battery, and Grid/Battery	NPC, LCOE, renewable fraction, operational CO_2 emissions, grid dependence, unmet load, and full reliability	—	Combines single-objective NPC minimization with comparative performance assessment under identical load, tariff, outage, and financial assumptions, while explicitly examining how the nominal discount rate, inflation rate, diesel fuel price, and PV derating factor influence residential hybrid system selection.

As shown in Table 1, previous studies have provided valuable insights into residential storage, hybrid system feasibility, and renewable energy planning; however, relatively limited attention has been given to a consistent comparative evaluation of multiple grid-connected residential hybrid architectures under combined tariff, outage, and macro-financial conditions. This is the main gap addressed by the present study.

Based on this positioning, the next section presents the methodological framework used to evaluate the candidate residential hybrid configurations under consistent technical, economic, and reliability assumptions.

2. Methodology

2.1. Study Framework

The overall study framework is presented in Figure 1. As illustrated, the analysis is structured around five sequential stages: case study inputs, candidate system architectures, HOMER Pro simulation and optimization, comparative performance evaluation, and sensitivity and trade off analysis. This framework was developed to provide a consistent basis for identifying cost-effective residential hybrid energy systems while also examining their environmental and reliability performance under the same technical and economic conditions. The case study inputs include the site location and solar resource data, the estimated residential load profile, the grid tariff and sell-back rate, the grid outage characteristics, the technical specifications of the system components, and the economic and financial assumptions. Based on these inputs, six grid-connected hybrid system architectures were defined for evaluation: Grid/Diesel, Grid/PV/Diesel, Grid/PV/Diesel/Battery, Grid/Diesel/Battery, Grid/PV/Battery, and Grid/Battery. All candidate configurations were simulated under identical load, resource, tariff, outage, and financial assumptions in order to ensure a consistent comparative basis. The framework was implemented in HOMER Pro software 3.18.4 to simulate and compare a large number of feasible system configurations under the specified technical and financial assumptions [41–47]. In the present study, the optimization is formulated as a single-objective problem in which net present cost (NPC) is minimized subject to technical and operational constraints, including

a zero unmet load requirement. The remaining indicators are not treated as additional optimization objectives; rather, they are used as comparative performance measures to evaluate the optimized configurations from broader techno-economic, environmental, and reliability perspectives. Accordingly, system performance was assessed using a set of key performance indicators, including NPC, levelized cost of energy (LCOE), renewable fraction, operational CO_2 emissions, electricity purchased from the grid, and unmet load. These indicators were selected to capture the main economic, environmental, and operational dimensions relevant to residential hybrid system selection.

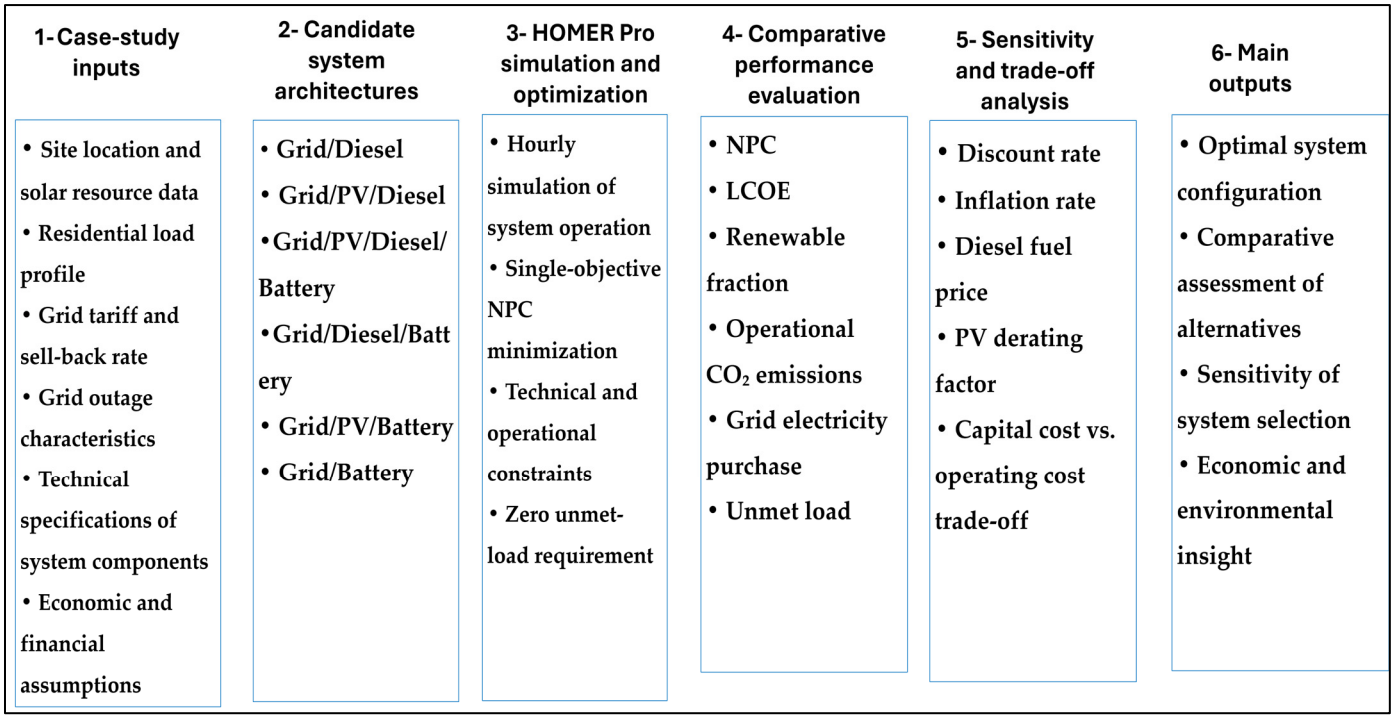


Figure 1. Integrated assessment framework for residential hybrid energy systems.

To examine the robustness of the results, a comprehensive sensitivity analysis was conducted for the principal uncertain parameters affecting system economics and configuration selection, namely the nominal discount rate, inflation rate, diesel fuel price, and PV derating factor. In particular, the PV derating factor was varied over the range 50–80% to assess how alternative assumptions regarding effective PV performance influence the preferred system design and its long-term economic outcomes. In addition, the analysis was extended to examine the trade off between capital investment and operating cost across the feasible solution space. In this way, the framework combines single-objective cost optimization with comparative system evaluation and sensitivity analysis to support a more comprehensive assessment of residential hybrid energy systems.

2.2. System Components

2.2.1. Solar Photovoltaic (PV) Array

The PV system shown in Figure 2 represents a flat plate fixed tilt photovoltaic has a rated capacity of 250 W and is connected to a direct current (DC) electrical bus, which is common for integrating with battery-based or hybrid systems. The capital cost is USD 611/kW and the replacement cost is 100% of the capital cost (Table 2). The fixed PV operation and maintenance cost of USD 14.6/kW/yr was adopted as an aggregate annual O&M estimate from the literature. This value represents routine maintenance activities but does not explicitly separate the additional cost of site-specific cleaning cycles. In

arid environments such as Fayoum, where dust accumulation may be more pronounced, more frequent panel cleaning could increase actual operating expenditures relative to standard reference values. Such cleaning practices may also be important for preserving effective PV performance over time. Nevertheless, because all PV-based configurations were evaluated under the same O&M assumption, the comparative results remain internally consistent within the adopted modeling framework. The present analysis adopts a base case PV derating factor of 80% to represent aggregate real-world performance losses, including soiling, temperature effects, wiring losses, and mismatch losses. Since the HOMER Pro 3.18.4 version used in this study does not support explicit multi year PV degradation simulation within the adopted modeling framework, the robustness of the results was further examined through a sensitivity analysis of the PV derating factor over the range 50–80%. This additional analysis was introduced to test the effect of more conservative assumptions regarding effective PV performance over the project lifetime. The present study assumes a fixed 25-year project lifetime with a static residential load profile. Accordingly, the analysis does not account for possible future growth in household electricity demand arising from changes in appliance ownership, occupancy behavior, or the electrification of new end uses.

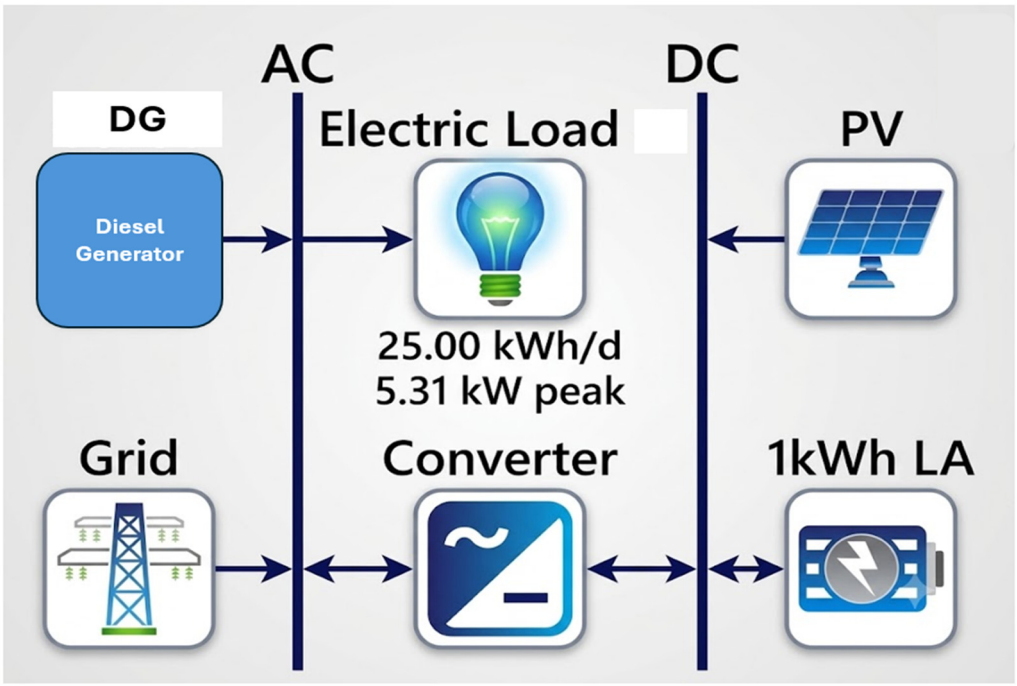


Figure 2. Schematic of the grid-connected hybrid PV/Diesel/Battery system for residential loads.

Table 2. Technical and economic specifications of PV module [48,49].

Technical Specifications	Values
Module	Mono-Si JKM-250 M
Module nominal efficiency	15.27%
Maximum power	250 W
Module area	1.637 m^2
Temperature coefficients	−1.106 W/°C
Capital cost of fixed tilt	611 USD/kW
Fixed operating cost of fixed tilt	14.6 USD/kW/yr
Replacement cost	100% of capital cost

2.2.2. Diesel Generator

The diesel generator is incorporated as a backup power source to support the load when the PV system and grid supply are insufficient and the battery charge is inadequate, thereby enhancing system reliability, particularly during grid outages. The generator capacity is automatically determined based on system requirements. Technical specifications, including fuel type (diesel), fuel consumption, and emissions data, are included to assess environmental impact. Economic parameters such as the initial capital cost (USD 500/kW), replacement cost (100% of the capital cost), operation and maintenance expenses (USD 0.03/h), and fuel price (USD 0.39/L) are incorporated into the lifecycle cost analysis. The fuel price reflects the current situation in Egypt [50]. Operational settings, including a minimum load ratio of 25%, a lifetime of 15,000 h, and AC bus connectivity, ensure realistic performance modeling. In HOMER Pro 3.18.4, the minimum generator load ratio prevents the diesel generator from operating at excessively low load, but it does not prevent shutoff. Therefore, if the required backup power falls below the specified 25% minimum load ratio, the generator operates at the minimum allowable output when committed, and any excess power can be directed to battery charging or otherwise absorbed by the system; if no generator power is required, the generator remains off. In addition, if the diesel generator is committed during a grid outage and required to operate at its minimum load ratio while the battery bank is already at 100% SoC, the surplus electricity is treated as excess electricity and is effectively dumped/curtailed by the system. Moreover, the optimization options enable the simulation of scenarios both with and without the generator.

2.2.3. Grid Characterization

The utility grid is treated as the primary source of electricity in all simulated configurations, and the model allows both electricity purchase from the grid and electricity export to the grid when applicable. To represent grid unreliability under the case study conditions, outages were modeled in HOMER Pro 3.18.4 using a stochastic random outage formulation (Figure 3). Specifically, the grid was characterized by a mean outage frequency of 180 outages/year, a mean repair time of 2.0 h per outage, and a repair time variability of 5%. Under this formulation, outage events are generated randomly across the annual simulation horizon, and therefore they are not explicitly concentrated during specific periods of the day or year, such as evening peak demand hours or summer high load months.

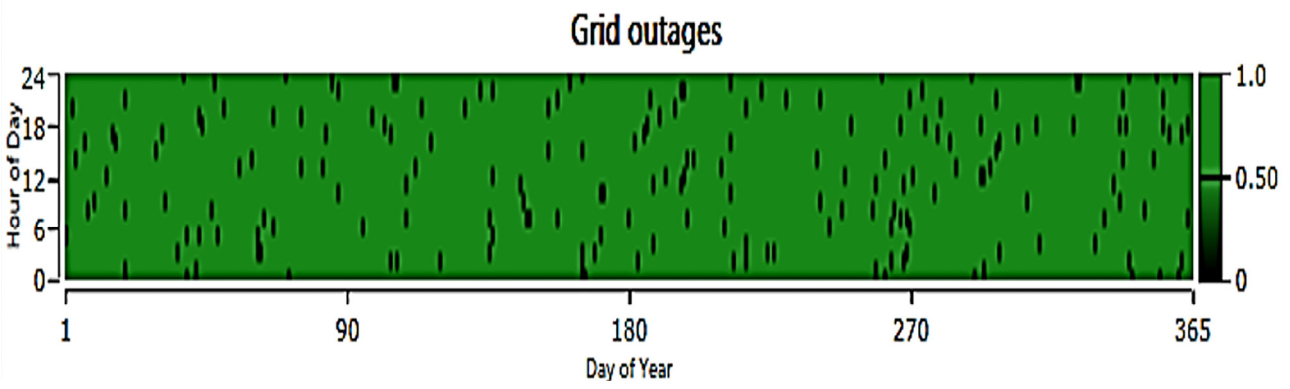


Figure 3. Frequent grid outages throughout the year.

This assumption provides a generalized reliability stress test for the hybrid system over the full year; however, it is important to interpret it carefully. Because the residential load profile exhibits a pronounced evening demand peak, outage clustering during those periods could impose more severe operating stress than the randomly distributed case considered here. In particular, repeated outages during high demand evening hours or

during the summer season could reduce the battery autonomy margin, increase battery cycling frequency, and lead to earlier reliance on diesel generator support in order to maintain full reliability. Although such critical period outage clustering was not explicitly modeled in the present study, it represents an important practical scenario for future reliability-oriented extensions of the framework.

To quantify the environmental impact of grid electricity purchases, an emission factor of 0.447 kg CO_2/kWh [51] was assigned to the Egyptian national grid within the HOMER Pro 3.18.4 model.

2.2.4. Grid Rate

The present study assumes a fixed time-of-use tariff schedule and a fixed grid sell-back rate. Table 3 presents the grid rate schedule interface for electricity purchased from the grid, with four customizable tariff rates ranging from USD 0.05/kWh to USD 0.25/kWh. The schedule shows how these rates are applied across different months, reflecting seasonal variations in electricity pricing. The data indicate a time-of-use pricing strategy, with higher rates applied during the summer months (May–August), likely due to increased cooling demand, while lower rates dominate during the winter season. This pattern highlights the relationship between climatic conditions, electricity demand, and pricing structures. In the Egyptian context, a grid sell-back rate of USD 0.014/kWh for electricity exported from the PV system to the grid is modeled based on annual net electricity purchases [52].

Table 3. Time-of-use grid electricity purchase rates in USD/kWh.

Time Period	January–April	May–October	November–December
00:00–12:00	0.10	0.10	0.10
12:00–16:00	0.05	0.10	0.05
16:00–21:00	0.20	0.25	0.20
21:00–23:59	0.10	0.10	0.10

2.2.5. Battery Storage

Lead–acid batteries were selected in this study as the baseline storage technology because they remain a cost accessible, commercially available, and widely adopted option in many residential and price sensitive applications. Their relatively low upfront cost [53] and practical availability make them a suitable reference technology for comparative techno-economic assessment. The purpose of the present study is not to determine the best battery chemistry in general, but to compare alternative hybrid system architectures under a consistent storage baseline. The technical specifications of the lead–acid battery storage system (Table 4) include a nominal voltage of 12 V, a nominal capacity of 1 kWh, and a round-trip efficiency of 80%. From an economic perspective, the battery has a capital cost of EUR 100/kWh and annual operation and maintenance costs of USD 8/year. In HOMER Pro 3.18.4, the lead–acid battery was modeled with a 14-year float life and a lifetime throughput of 800 kWh. Thus, battery replacement was not based solely on calendar life; rather, HOMER accounted for degradation through cumulative energy throughput, with storage life determined by the applicable time and/or throughput constraints defined in the model. Additionally, the initial state of charge is set at 100%, while the minimum state of charge is maintained at 20%.

Table 4. The characterization of the battery storage system.

Item	Value	Unit
Capacity	1.0	kWh
Lifetime	14 [53]	years
Throughput	800	kWh
Capital cost *	100 [53]	EUR/kWh
Replacement cost	100% of capital cost	USD
Minimum state of charge	20	%
Maximum state of charge	100	%
Round-trip efficiency	80	%
Operation and maintenance cost	8.0	USD/year

* Average exchange rate 1 EUR = 1.05 USD.

2.2.6. Converter

A bidirectional converter is utilized to manage the power flow between the AC and DC components of the system, ensuring compatibility and efficient integration among the various system elements. The capital cost of the converter is set at USD 300/kW, with the replacement cost assumed to be 100% of the capital cost, and a lifetime of 15 years.

2.3. Site Characteristics and Resource Assessment

To validate the proposed framework in a real-world context, this study considers a residential case in Fayoum, Egypt (29.30° N, 30.84° E). Fayoum was selected not only because of its favorable solar resource and grid reliability concerns, but also because it provides a representative residential prosumer environment in which several important design drivers occur simultaneously. These include strong seasonal solar availability, pronounced evening household demand peaks, dependence on-grid electricity under interruption risk, and an investment environment in which lifecycle cost, financing conditions, and backup requirements significantly influence system selection. Therefore, Fayoum offers a relevant case study setting for examining the combined techno-economic, environmental, and reliability performance of residential hybrid energy systems, while also allowing the proposed framework to generate insights applicable to other regions with similar operating conditions.

Solar potential, which is a key driver for PV integration, was quantified using 19-year average (2005–2023) global horizontal irradiance (GHI) data obtained from the PVGIS database [54]. Figure 4 illustrates the monthly variation in average daily solar radiation and clearness index, revealing a pronounced seasonal pattern in the solar resource availability. Daily solar radiation increases steadily from about 3.3 kWh/m^2/day in January to a peak of approximately 8.3 kWh/m^2/day in June, remains high in July and August, and then declines gradually to nearly 3.0 kWh/m^2/day in December. A similar trend is observed for the clearness index, which rises from roughly 0.55 in January to its maximum value of about 0.74 in July, before decreasing again toward the end of the year. The close correspondence between the two parameters indicates that periods of higher atmospheric transparency are associated with greater incident solar energy, particularly during the late spring and summer months. This seasonal behavior confirms that the strongest photovoltaic energy potential occurs between May and August, whereas the lower values recorded in winter suggest reduced solar availability and a greater reliance on complementary sources such as the grid, diesel generator, or battery storage. Overall, the

figure demonstrates that solar resource conditions are highly favorable during the mid-year, which has important implications for the optimal sizing and operation of the proposed hybrid PV/Diesel/Battery system.

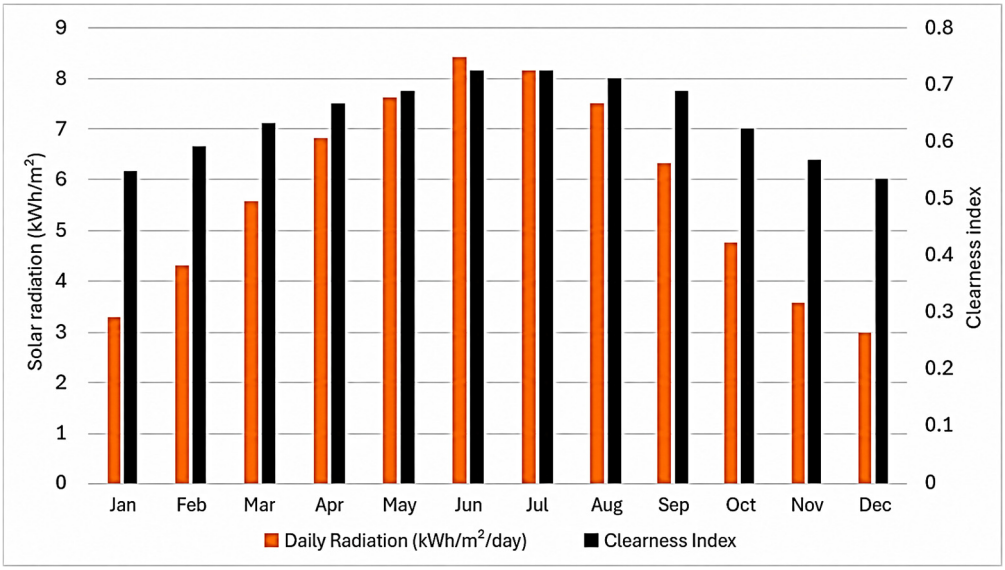


Figure 4. Monthly solar resource and clearness index data for the selected site.

After establishing the site characteristics and renewable resource conditions, the residential electricity demand profile is defined, as it drives both system sizing and operational performance.

2.4. Load Profile

Table 5 presents the monthly energy consumption (kWh) and monthly peak load (kW) for the case study household. The residential load profile was established from measured on site data collected throughout the year from a residential building in Fayoum and was modeled at an hourly time step resolution (60 min). The corresponding annual electricity consumption, peak load, and load factor were 9125 kWh/year, 5.31 kW, and 0.20, respectively.

Table 5. Monthly energy consumption and monthly peak load.

Month	Energy (kWh)	Peak (kW)
January	611	3.42
February	565	3.10
March	713	3.79
April	756	4.30
May	832	4.26
June	883	4.22
July	925	4.82
August	936	5.31
September	836	4.56
October	759	3.96
November	668	4.17
December	641	3.21
Annual	9125	5.31

The monthly load data show clear seasonal variation in household electricity demand. Monthly energy consumption increases from 611 kWh in January and 565 kWh in February to a summer maximum of 936 kWh in August, before declining again to 641 kWh in December. This pattern indicates that the household load is strongly influenced by seasonal conditions, with the highest electricity use occurring during the hot summer months, most likely because of increased cooling demand. The monthly peak load follows a similar seasonal pattern, rising from 3.10 to 3.42 kW in winter to a maximum of 5.31 kW in August, before declining again during the cooler months.

Figure 5 presents the monthly hourly residential load profiles for the case study and reveals a consistent diurnal demand pattern with clear seasonal variation. In all months, electricity demand remains low during the late night and early morning hours, begins to increase after approximately 06:00, and exhibits moderate daytime consumption, followed by a pronounced evening peak during the 18:00–21:00 period. This recurring evening maximum is characteristic of residential electricity use and is likely associated with increased occupancy, lighting demand, cooking activity, and the operation of household appliances after sunset. Seasonal differences are also evident, with higher loads observed during the warmer months, particularly from June to August, indicating the additional contribution of cooling-related demand, whereas winter months exhibit lower and flatter profiles.

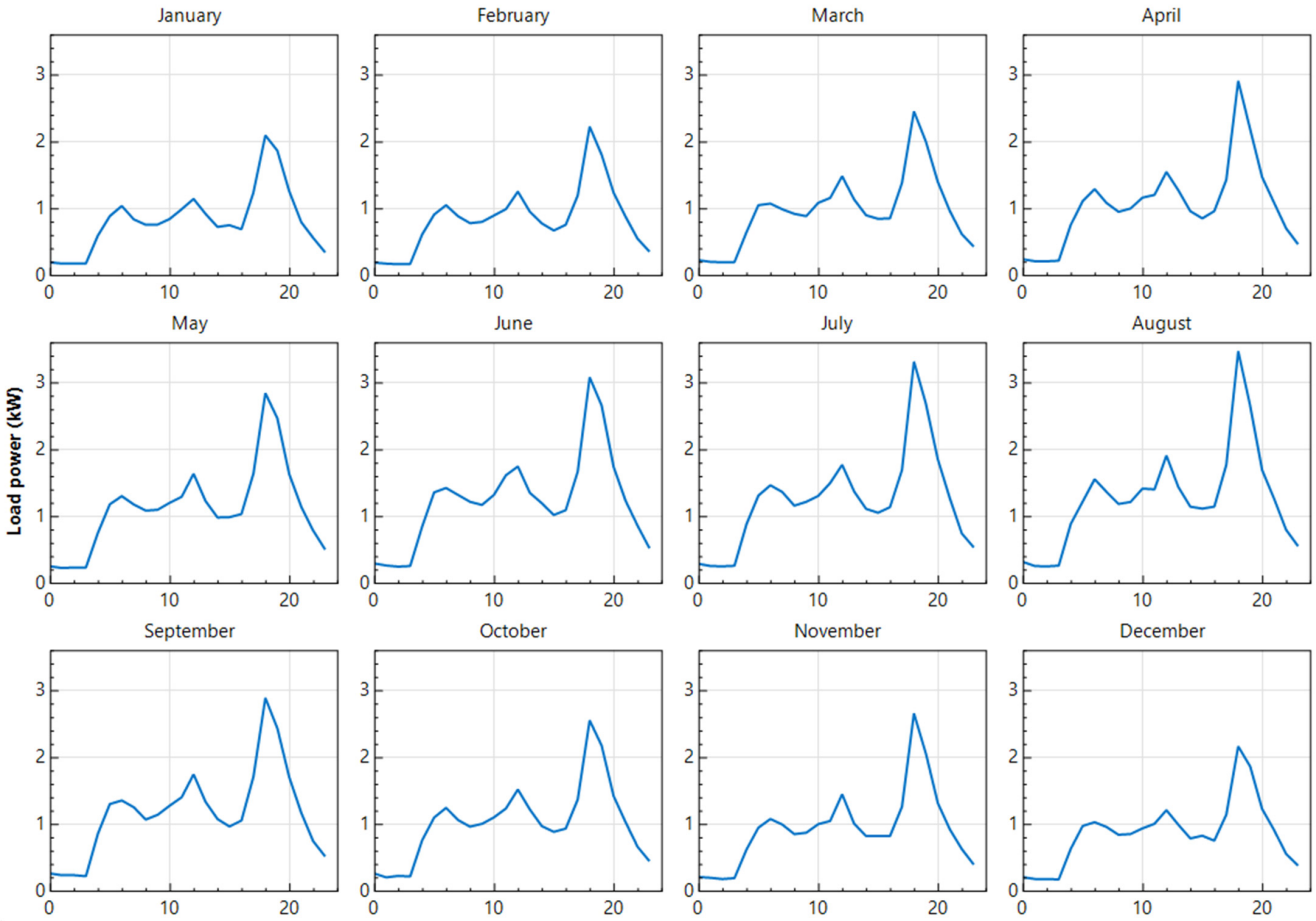


Figure 5. Monthly hourly residential load profiles for the case study.

The persistence of the evening peak across all seasons highlights a temporal mismatch between peak household demand and solar PV generation, which occurs during daylight hours. This load behavior therefore justifies the inclusion of battery storage, grid support, and diesel backup in the proposed hybrid system in order to maintain reliable supply during evening peak demand periods and under conditions of limited solar availability.

3. Optimization Approach

Figure 6 illustrates the high-level hourly dispatch and feasibility screening logic used to represent the operation of the grid-connected residential hybrid energy system simulation model. At each hourly time step h, the model reads the load demand $L(h)$, PV output $PV(h)$, grid availability status, battery charge, and component operating limits. When the grid is available, the load is supplied by the grid, and available PV output is exported to the grid according to the adopted sell-back arrangement. When the grid is unavailable, the backup/support hierarchy is activated. In this case, PV generation is used first to satisfy the load. If PV generation exceeds the load, the excess energy is used to charge the battery whenever storage capacity is available; otherwise, it is recorded as dumped/excess energy. If PV generation is insufficient, the remaining load is supplied from the battery when sufficient charge is available. If the battery cannot fully satisfy the remaining demand, the diesel generator is dispatched to supply the residual load. Any diesel generation exceeding the remaining load is directed to battery charging when possible; otherwise, it is recorded as dumped/excess energy.

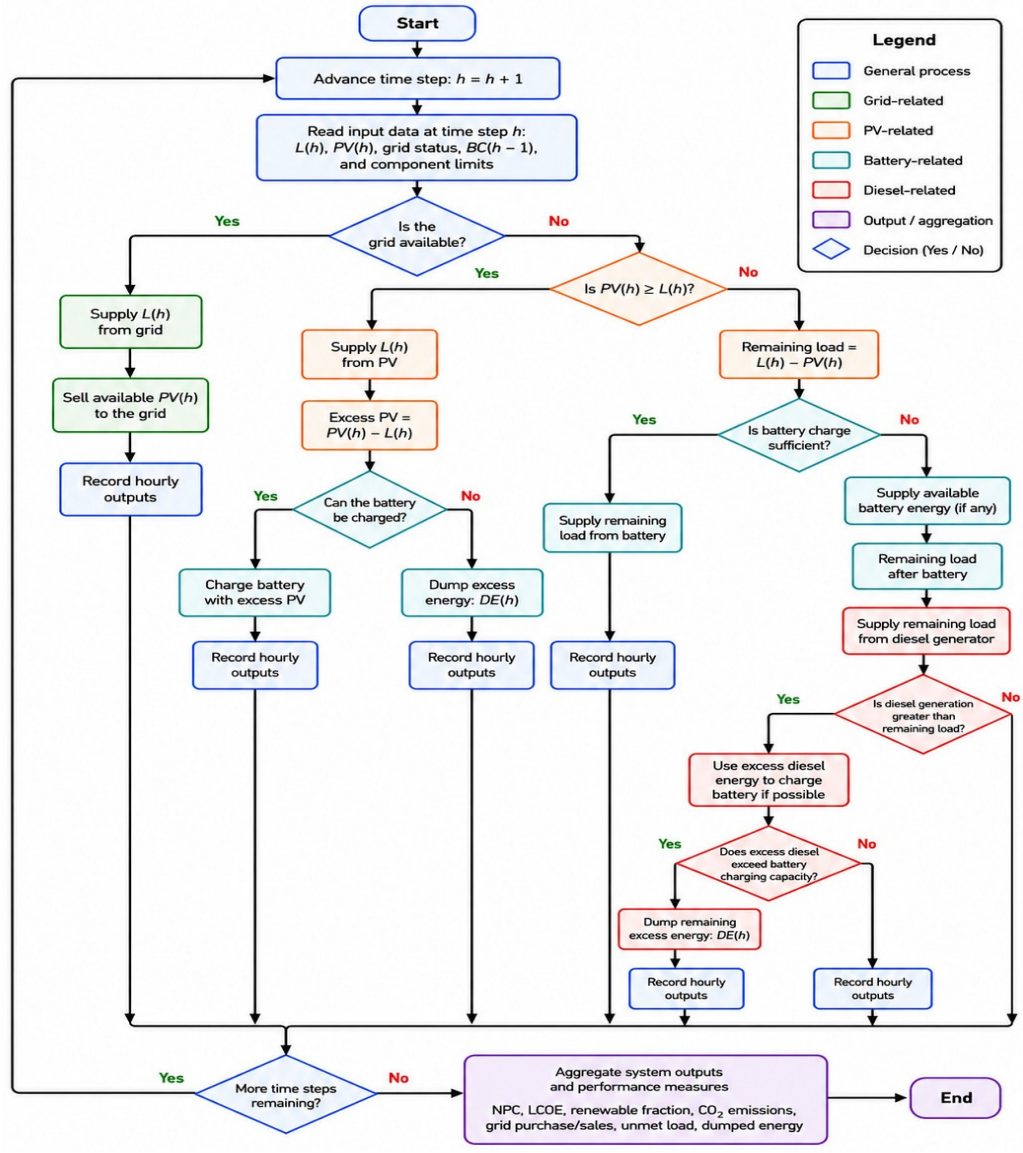


Figure 6. High-level hourly dispatch and feasibility screening logic of the grid-connected residential hybrid energy system simulation model.

The recorded hourly outputs include grid electricity purchase/export, PV utilization, battery charging/discharging, diesel generation, unmet load, dumped/excess energy, and operational emissions. After completing the hourly simulation over the full study horizon, these outputs are aggregated to calculate the annual performance indicators, including NPC, LCOE, renewable fraction, operational CO_2 emissions, grid electricity purchase/export, operating cost, and unmet-load ratio. Within the HOMER Pro 3.18.4 framework, the internal simulation and optimization/search procedure evaluates candidate system configurations and component size combinations within the specified technical and economic bounds. Configurations that do not satisfy the prescribed service level constraint, represented by the maximum allowable unmet load ratio, are treated as infeasible. Feasible configurations are then ranked according to NPC, which is the single optimization objective in this study, while LCOE, renewable fraction, operational CO_2 emissions, grid electricity purchase/export, and other indicators are used for comparative performance assessment.

3.1. NPC-Based Optimization Model, Decision Variables, and Constraints

3.1.1. Objective Function

The optimization problem is formulated as a single-objective NPC-minimization model. The objective is to minimize the NPC of each candidate hybrid energy-system configuration over the project lifetime, subject to the technical and reliability constraints. The NPC includes the initial capital cost, operation and maintenance cost, diesel fuel cost, replacement cost, and revenue from electricity exported to the grid. It is expressed as [55]:

$$Minimize \;\; NPC = C_{cap} + \sum_{t=1}^{T} \left[\frac{C_{op}(t) + Cfuel(t) + RC(t) - RV(t)}{\left(\frac{d-f}{1+f} + 1\right)^{t}} \right] \quad (1)$$

where C_{cap} is the initial capital cost of the system components, including the PV array, diesel generator, battery bank, and converter; $C_{op}(t)$ is the operation and maintenance cost in year t; $Cfuel(t)$ is the diesel fuel cost in year t; $RC(t)$ is the replacement cost incurred in year t; $RV(t)$ is the revenue from electricity exported to the grid in year t; d is the nominal discount rate; f is the inflation rate; T is the total project lifetime; and t is the year index.

In this formulation, the term $\left(\frac{d-f}{1+f}\right)$ represents the real discounting factor derived from the nominal discount rate and inflation rate. Accordingly, the annual cost and revenue terms in Equation (1) should be interpreted consistently with the adopted economic assumptions to avoid double counting inflation effects.

3.1.2. Design and Operational Variables

The main design variables are the installed PV capacity, P_{pv}; the installed diesel-generator capacity, P_{DG}; and the battery size, expressed as the number of battery units. For configurations in which a component is not included, the corresponding design variable is fixed at zero.

The hourly operational variables include PV electricity supplied to the load, electricity purchased from the grid, electricity exported to the grid, battery charge and discharge energy, diesel-generator output, excess electricity, and unmet load. These variables are determined during the hourly simulation for each candidate configuration and component size combination.

3.1.3. Reliability Constraint

To ensure supply adequacy under the modeled grid outage conditions, all candidate configurations were evaluated subject to a zero unmet load requirement. The unmet load ratio is defined as:

$$load_{unmet} = \frac{\sum_{h=1}^{H} E_{unserved}(h)}{\sum_{h=1}^{H} E_{load}(h)} \quad (2)$$

and the reliability constraint is imposed as:

$$load_{unmet} \leq \epsilon \quad (3)$$

where $E_{unserved}(h)$ is the unserved electrical demand at hour h, $E_{load}(h)$ is the total electrical load demand at hour h, and H is the total number of hourly time steps in the annual simulation. Any candidate solution with $load_{unmet} > \epsilon$ is considered infeasible under the zero unmet load requirement.

3.1.4. Component Capacity Bounds

For reproducibility, the HOMER Pro 3.18.4 model was simulated at an hourly resolution of 60 min using a Focus Factor of 50 and a Maximum Simulations per Optimization of 10,000. The optimization search was constrained by explicit lower and upper bounds on the main design variables. The PV capacity was bounded as:

$$0 \leq P_{pv} \leq 10 \text{ kW} \quad (4)$$

where the upper limit of the PV capacity reflects the available installation area of the residential building. The diesel generator capacity was bounded as:

$$0 \leq P_{DG} \leq 5\text{kW} \quad (5)$$

where the upper limit represents a practical residential-scale backup capacity.

The battery bank size, N_{bat}, was searched within the discrete range specified in the component settings of the HOMER Pro 3.18.4 model. Grid electricity purchase was modeled without an upper power-purchase limit, consistent with the grid-connected residential setting.

3.2. Financial Parameters Defining the Optimization Problem

The optimization is governed by a set of financial and reliability parameters that directly reflect the challenging economic and operational context. These parameters are not generic defaults but are chosen to quantify the influence of macro-financial conditions on system design.

- Nominal discount rate assumption: A high nominal discount rate assumption of 28.25% was adopted to reflect the prevailing macroeconomic and borrowing conditions relevant to medium-risk private energy projects in Egypt [56]. Although this assumption makes the analysis more representative of local financing conditions, it has an important methodological implication: a high discount rate disadvantages technologies with substantial up-front capital requirements by reducing the present value of future operating cost savings. As a result, capital-intensive options such as PV and battery storage are placed at a relative disadvantage compared with lower CAPEX, higher OPEX alternatives such as diesel-based systems. This effect is central to the interpretation of the results and provides an important rationale for the sensitivity analysis, which examines how the preferred system configuration shifts under different financing conditions.

- Inflation Rate: Set at 9.4%, consistent with recent historical averages for Egypt [56]. This affects the escalation of future fuel and O&M costs, interacting with the discount rate in the NPC calculation.

In combination, these parameters define the objective function and constraints for the life cycle cost analysis, enabling the calculation of the NPC and LCOE for each system configuration. More importantly, they allow the model to capture the central trade off between achieving zero unmet load and minimizing system cost under high capital cost conditions.

On the basis of the above assumptions, constraints, and evaluation criteria, the following section presents the techno-economic and environmental results of the optimized system configurations.

4. Results and Discussion

4.1. Technical Performance Comparison

Table 6 compares the technical performance of the six proposed system configurations, namely Grid/PV/Battery, Grid/Diesel, Grid/PV/Diesel, Grid/PV/Diesel/Battery, Grid/Diesel/Battery, and Grid/Battery. A key observation is that all configurations achieved 0% unmet load, indicating that each system was technically capable of supplying the required demand without reliability violations. Therefore, the main distinction among the alternatives lies not in supply adequacy, but in the extent of grid dependence and the contribution of renewable generation. Among the evaluated options, the Grid/PV/Battery configuration demonstrates the strongest technical performance. This system incorporates 3.93 kW of PV and 13 battery units, resulting in the lowest annual grid electricity purchase of 5218 kWh. This indicates that a sufficiently sized combination of solar generation and battery storage can significantly reduce dependence on the utility grid while maintaining full reliability. In contrast, the Grid/Battery configuration, despite including 12 battery units, still requires the highest grid purchase at 9256 kWh, showing that storage alone cannot effectively reduce grid dependency in the absence of adequate renewable generation.

The diesel-based systems also exhibit limited technical advantages. Both the Grid/Diesel and Grid/PV/Diesel configurations require substantial grid imports of 8308 kWh and 8258 kWh, respectively. Within the constrained diesel generator search space, HOMER Pro selected the 5 kW upper bound for the diesel-based configurations, indicating that the maximum allowable generator size within the defined residential range was preferred to satisfy the full reliability requirement under the modeled outage and seasonal demand conditions. This result should therefore be interpreted as the optimum within the imposed design bounds, rather than as an unconstrained generator size determined solely by peak demand.

It can be observed that the PV capacity selected in the Grid/PV/Diesel configuration is negligible (0.033 kW) and therefore too small to have a meaningful impact on system operation. Likewise, the Grid/PV/Diesel/Battery configuration shows some reduction in grid electricity purchase to 7883 kWh, but this improvement remains modest compared with the Grid/PV/Battery system. The negligible PV capacity selected in the Grid/PV/Diesel configuration, 0.033 kW, should be interpreted as an economically consistent optimization outcome rather than a modeling error. The low grid sell-back rate of 0.014 USD/kWh makes electricity export commercially unattractive, while the absence of battery storage prevents surplus daytime PV generation from being shifted to the nighttime peak demand period. Moreover, the combined availability of grid supply and diesel backup already satisfies the full reliability requirement, reducing the economic value of additional PV capacity in this configuration. Under these conditions, and particularly under the adopted high discount rate environment, the optimizer finds little economic justification for meaningful PV investment in this configuration. In contrast, the Grid/PV/Battery configuration can

store daytime PV surplus and shift it to evening demand and outage periods, thereby greatly increasing the value of PV generation and leading to the selection of a much larger PV capacity.

Table 6. Techno-economic and environmental performance of optimized hybrid system configurations.

Configuration	Grid/PV/Battery	Grid/Diesel	Grid/PV/Diesel	Grid/PV/Diesel/ Battery	Grid/Diesel/ Battery	Grid/Battery
Performance Comparison						
PV (kW)	3.93	0	0.033	0.306	0	0
Diesel Gen. (kW)	0	5	5	5	5	0
Battery (1 kWh units)	13	0	0	1	1	12
Grid purchase (kWh)	5218	8308	8258	7883	8297	9256
Unmet Load (%)	0	0	0	0	0	0
Economic comparison						
NPC (USD)	8949	9355	9359	9509	9534	9712
LCOE (USD/kWh)	0.135	0.18	0.18	0.183	0.183	0.187
Initial Capital (USD)	5257	2500	2531	2875	2621	2153
Operating Cost (USD/yr)	648.19	1204	1199	1165	1214	1327
Environmental comparison						
CO_2 Emissions (kg/yr)	2333	4616	4593	4400	4611	4138
Renewable Fraction (%)	55.1	0	0.5	3.41	0	0

Note: Renewable fraction represents the percentage of the total electrical load supplied by renewable generation within each configuration. Where emission reduction is discussed in the text, the Grid/Diesel configuration is used as the reference (base) system for comparison.

These results suggest that technical performance gains remain limited when diesel generation or marginal renewable capacity is added, unless the system achieves a sufficiently high level of PV penetration.

Overall, the technical performance comparison indicates that the Grid/PV/Battery system offers the most balanced and technically effective solution, as it satisfies the load reliably while minimizing reliance on imported grid electricity.

4.2. Economic Performance Comparison

The economic performance indicators in Table 6 clearly identify the Grid/PV/Battery configuration as the most cost-effective option over the project lifetime. Although this system has the highest initial capital cost of USD 5257, it achieves the lowest NPC of USD 8949 and the lowest LCOE of USD 0.135/kWh among all configurations. This finding indicates that higher initial investment in PV and battery storage is economically justified when evaluated from a life cycle perspective.

The main reason for this superior economic performance is the substantial reduction in annual operating expenditure. The Grid/PV/Battery system records an operating cost of only USD 648.19/yr, which is significantly lower than that of all other alternatives. By comparison, the Grid/Diesel and Grid/PV/Diesel systems have operating costs of USD 1204/yr and USD 1199/yr, respectively, while the Grid/Battery system shows the highest annual operating cost of USD 1327/yr. This confirms that diesel use and heavy reliance on-grid electricity increase long-term expenditure, even when initial capital requirements appear lower.

The results further show that lower capital cost does not necessarily translate into better economic performance. For example, the Grid/Diesel system requires only USD 2500 in initial investment, yet its NPC rises to USD 9355, which is substantially higher than that of the Grid/PV/Battery configuration. A similar pattern is observed for Grid/PV/Diesel and Grid/PV/Diesel/Battery, whose NPC values are USD 9359 and USD 9509, respectively. The Grid/Battery system also performs poorly economically, despite a moderate initial cost of USD 2153, because it remains highly dependent on purchased grid electricity and consequently incurs the highest operating cost and LCOE (USD 0.187/kWh).

These findings show that the economic optimum is determined not by minimizing upfront cost, but by achieving the best balance between capital investment and long-term savings. In this regard, the Grid/PV/Battery system provides the most favorable economic outcome and can therefore be considered the optimal configuration from a techno-economic perspective.

4.3. Environmental Performance Comparison

The environmental assessment presented in Table 6 is based on annual operational CO_2 emissions and the renewable fraction. In the present study, environmental performance is evaluated only in terms of operational CO_2 emissions resulting from grid electricity consumption and diesel fuel use during system operation. Accordingly, embodied emissions associated with the manufacturing, transportation, installation, replacement, and end-of-life treatment of PV modules, batteries, converters, and diesel generators were not considered.

The results show a clear environmental advantage for configurations with higher renewable penetration, particularly the Grid/PV/Battery system. This configuration produces the lowest annual CO_2 emissions of 2333 kg/yr and achieves the highest renewable fraction of 55.1%, demonstrating its strong potential to reduce carbon intensity while maintaining a reliable energy supply. In contrast, the systems with no meaningful PV contribution exhibit considerably higher emissions. The Grid/Diesel and Grid/Diesel/Battery configurations produce 4616 kg/yr and 4611 kg/yr of CO_2, respectively, while both have a 0% renewable fraction. This indicates that the addition of diesel generation and small-scale battery storage does not deliver environmental improvement when renewable generation is absent. Similarly, the Grid/Battery system emits 4138 kg/yr, which remains substantially higher than the Grid/PV/Battery option, again confirming that battery storage alone cannot ensure low-emission operation.

The Grid/PV/Diesel and Grid/PV/Diesel/Battery configurations provide only limited environmental benefits. Although the Grid/PV/Diesel/Battery system reduces emissions slightly to 4400 kg/yr, its renewable fraction remains very low at 3.41%, indicating that its PV capacity is insufficient to significantly displace conventional energy sources. The Grid/PV/Diesel system performs similarly poorly, with emissions of 4593 kg/yr and a negligible renewable fraction of 0.5%. These results suggest that minor additions of PV capacity do not yield substantial environmental gains unless renewable penetration is sufficiently high to meaningfully reduce dependence on-grid electricity and diesel generation.

Overall, the environmental comparison confirms that the Grid/PV/Battery configuration is the most sustainable option. Its significantly lower carbon emissions and much higher renewable fraction indicate that it is not only economically attractive but also environmentally preferable, making it the most suitable system for sustainable hybrid energy planning.

4.4. Operational Characteristics of the Optimal Configuration

As shown in Table 7, the additional HOMER Pro 3.18.4 outputs further explain the superior performance of the Grid/PV/Battery configuration. The system meets an annual load of 9125 kWh/yr with 7145 kWh/yr of PV generation, indicating a strong renewable contribution. The 13 kWh battery supports temporal shifting of solar energy, as reflected by its annual input (925 kWh/yr), output (741 kWh/yr), and throughput (828 kWh/yr), thereby reducing dependence on the grid during non-solar hours. At the same time, the system exports 2500 kWh/yr to the grid and records only 157 kWh/yr of excess electricity, showing that most PV generation is effectively utilized. The absence of diesel capacity, operating hours, and fuel consumption confirms that diesel backup is not required in the optimal configuration. Consequently, the reported 2333 kg/yr of CO_2 emissions arise entirely from grid electricity purchases. Overall, these results demonstrate that the superior performance of the Grid/PV/Battery system is driven by the combined effect of substantial PV generation, battery supported load shifting, and complete elimination of diesel use.

Table 7. Detailed HOMER Pro outputs for the optimal configuration.

Indicator	Value
Annual load (kWh/yr)	9125
Annual PV generation (kWh/yr)	7145
Electricity purchased from grid (kWh/yr)	5218
Electricity sold to grid (kWh/yr)	2500
Excess electricity (kWh/yr)	157
Battery nominal capacity (kWh)	13
Annual battery throughput (kWh/yr)	828
Battery energy in (kWh/yr)	925
Battery energy out (kWh/yr)	741
Diesel generator capacity selected (kW)	0
Diesel operating hours (h/yr)	0
Annual diesel consumption (L/yr)	0
Grid related CO_2 emissions (kg/yr)	2333
Diesel related CO_2 emissions (kg/yr)	0

4.5. Comparison of the Optimal Grid/PV/Battery System with Alternative Configurations

As summarized in Table 8, the optimal Grid/PV/Battery configuration outperforms the remaining candidate systems across the main performance indicators. Relative to the alternative configurations, the optimal system reduces NPC by approximately 4.3–7.9%, lowers LCOE by 25.0–27.8%, and decreases annual operating cost by 44.4–51.2%. It also achieves a reduction in operational CO_2 emissions of 41.5–48.0%. With respect to renewable contribution, the renewable fraction improves by 51.69–55.10 percentage points compared with the other cases. These results further confirm the clear techno-

economic and environmental superiority of the Grid/PV/Battery configuration under the adopted assumptions.

Although the base case results identify the preferred configuration under the adopted assumptions, additional insight can be obtained by assessing the sensitivity of these findings to variations in key technical and financial parameters.

Table 8. Comparative improvement of the optimal Grid/PV/Battery system over the other configurations.

Reference Configuration	NPC Reduction (%)	LCOE Reduction (%)	Operating Cost Reduction (%)	Renewable Fraction Improvement (%)	CO_2 Reduction (%)
Grid/Diesel	4.34	25.00	46.16	55.10	47.96
Grid/PV/Diesel	4.38	25.00	45.94	54.60	47.70
Grid/PV/Diesel/Battery	5.89	26.23	44.36	51.69	45.41
Grid/Diesel/Battery	6.14	26.23	46.61	55.10	47.91
Grid/Battery	7.86	27.81	51.15	55.10	41.51

4.6. Sensitivity Analysis

4.6.1. Sensitivity of Net Present Cost

Figure 7 illustrates the sensitivity of the total net present cost to variations in the nominal discount rate, inflation rate, and diesel fuel price. The nominal discount rate is the most influential parameter, producing a pronounced inverse relationship with NPC, which indicates that the economic viability of the system is highly dependent on the assumed time value of money. Conversely, the expected inflation rate has a direct positive effect on NPC, reflecting the increase in discounted lifecycle expenditures under higher inflation scenarios. In contrast, diesel fuel price has an almost negligible effect on NPC over the examined range (0.30–0.90 USD/L), as evidenced by the nearly constant response. This sensitivity reflects the low reliance on diesel-based generation in the optimal system design, thereby enhancing the system's resilience to fuel price volatility and broader fuel market uncertainty. These results confirm that financial parameters dominate the economic performance of the hybrid energy system, while fuel price uncertainty is of secondary importance. A key practical implication of the sensitivity analysis is that the future competitiveness of residential hybrid systems depends more strongly on financing conditions and macro-financial stability than on diesel price fluctuations. For planners and policymakers, this means that supportive financing mechanisms, investment risk reduction, and long-term policy stability are likely to be more influential than fuel price trends in promoting cost-effective residential renewable energy deployment.

4.6.2. Sensitivity of Optimal System Selection to Financial Conditions

To further examine the effect of financing conditions, the sensitivity analysis was expanded to include nominal discount rate values ranging from 8% to 28% (see Figure 8), thereby covering both moderate and highly constrained investment environments. The resulting optimal system map indicates that the Grid/PV/Battery configuration remains the preferred solution across most of the examined parameter space, particularly under moderate nominal discount rate conditions. In contrast, the Grid/Diesel system becomes optimal only near the highest nominal discount rate range, where the heavy penalty on upfront capital cost reduces the attractiveness of PV and battery investment. A limited region of the solution space also favors the Grid/PV/Diesel/Battery configuration under the combination of a low nominal discount rate and high inflation. Overall, these results

confirm that improved financing conditions strengthen the competitiveness of capital-intensive PV/Battery systems.

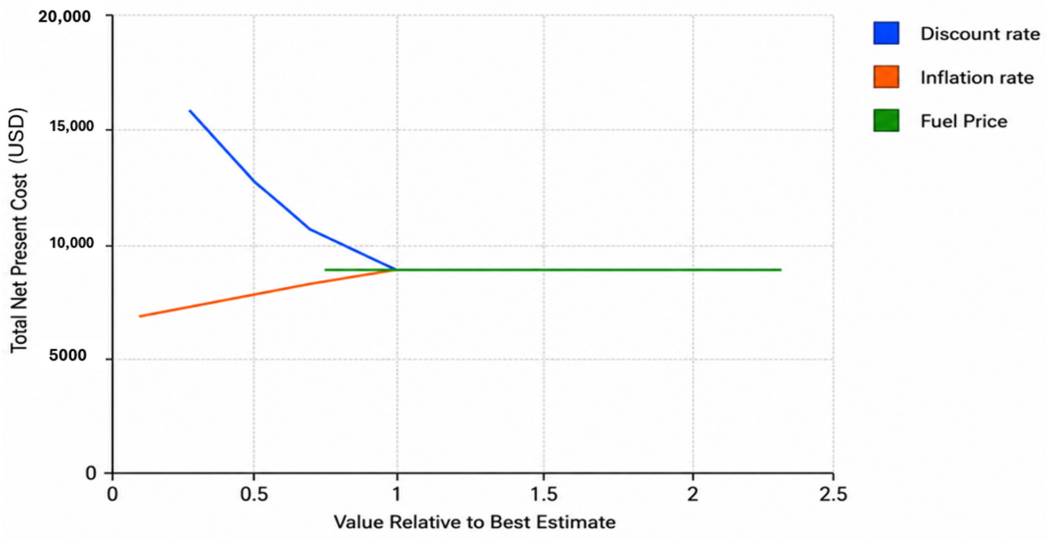


Figure 7. Sensitivity of the total net present cost to variations in the nominal discount rate, expected inflation rate, and diesel fuel price.

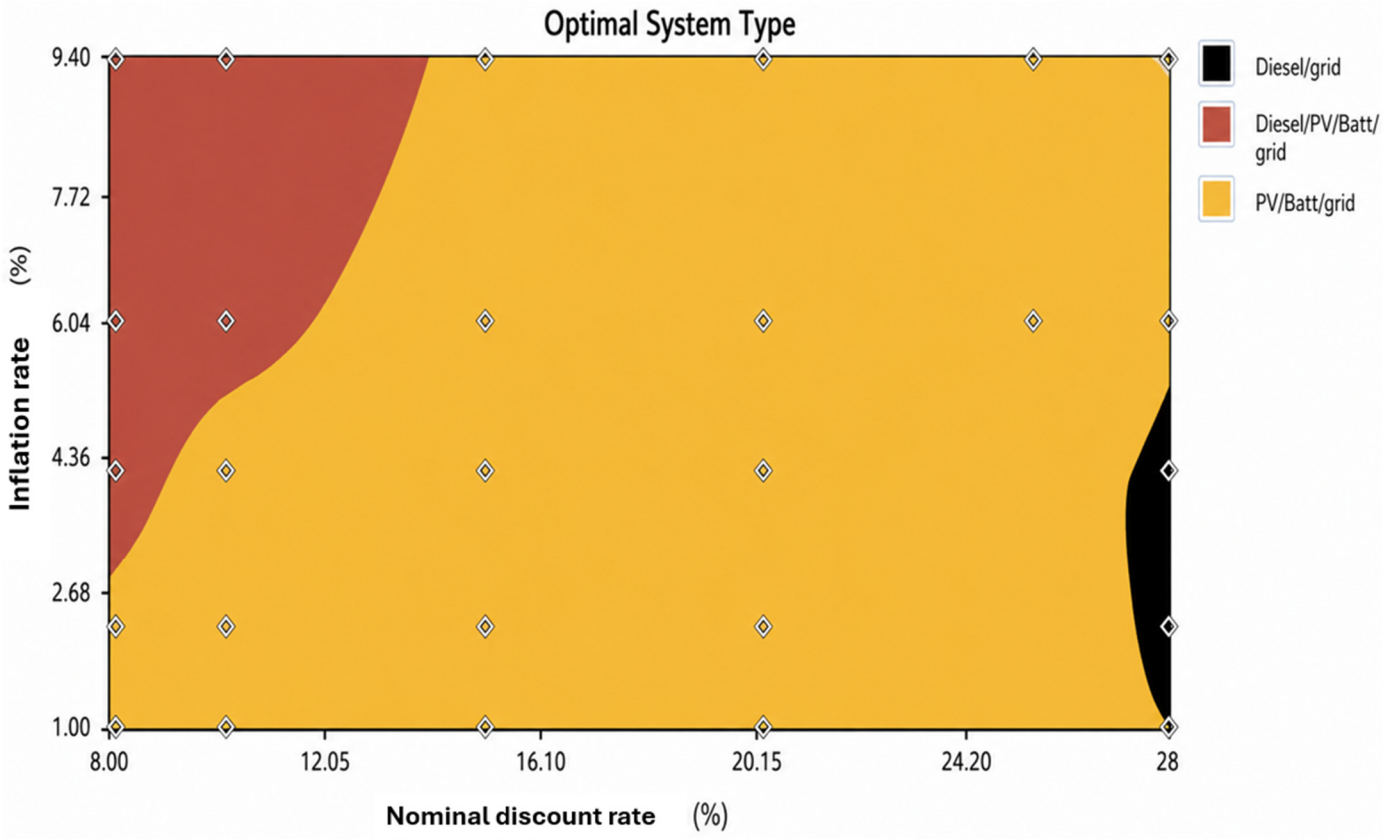


Figure 8. Sensitivity of optimal hybrid system selection to nominal discount rate and inflation rate.

4.6.3. Economic Trade off Between Capital and Operating Costs

Figure 9 illustrates the relationship between total operating cost and total capital cost for the feasible hybrid system configurations generated during the optimization process. A clear trade off is evident between these two economic indicators. Configurations with low operating cost are generally associated with high capital cost, indicating that greater upfront investment in system components such as PV and battery storage can substantially

reduce recurring fuel, grid purchase, and maintenance expenses. Conversely, systems with lower capital cost tend to incur higher operating costs, reflecting greater dependence on external electricity supply and/or conventional backup generation over the project lifetime. The distribution of points also reveals a nonlinear pattern, with a minimum capital cost region occurring at intermediate to high operating costs, beyond which capital cost rises slightly again for some solutions. This distribution suggests the existence of several feasible design combinations with differing component sizes and dispatch characteristics. Overall, the figure highlights the fundamental economic compromise between initial investment and long-term operational expenditure, confirming the importance of integrated techno-economic optimization in identifying the most cost-effective hybrid system configuration.

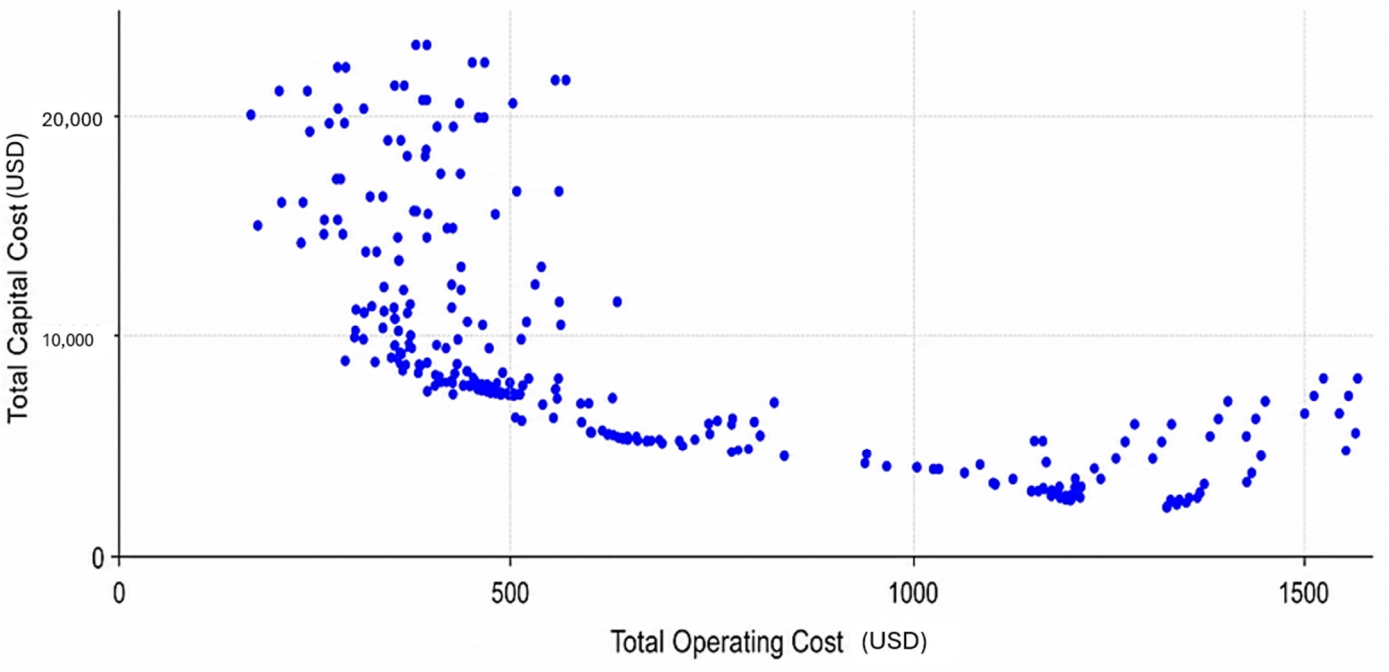


Figure 9. Scatter plot of total operating cost versus total capital cost.

4.6.4. Sensitivity Analysis of the PV Derating Factor

Table 9 shows that the optimal system configuration is sensitive to the assumed PV derating factor. At PV derating levels of 50% and 60%, the optimal solution shifts to the Grid/Diesel configuration, whereas at PV derating levels of 70% and 80%, the Grid/PV/Battery configuration becomes optimal. The most favorable economic performance is achieved at an 80% derating factor, where the Grid/PV/Battery system records the lowest NPC and LCOE.

Table 9. Sensitivity of the optimal hybrid system to the PV derating factor.

PV Derating Factor (%)	Optimal Configuration	PV (kW)	Diesel Generator (kW)	Battery Capacity (1 kWh Units)	NPC (USD)	LCOE (USD/kWh)
50	Grid/Diesel	0.00	5.00	0	9355	0.180
60	Grid/Diesel	0.00	5.00	0	9355	0.180
70	Grid/PV/Battery	2.70	0.00	12	9341	0.170
80	Grid/PV/Battery	3.93	0.00	13	8949	0.135

The preceding analysis identified the preferred system configuration and clarified the principal drivers of its performance. The following conclusion summarizes the main implications of these findings, outlines the study's contributions and limitations, and identifies directions for future research.

5. Conclusions

This study addressed the problem of identifying a cost-effective, reliable, and lower-emission residential hybrid energy system under realistic technical, tariff, outage, and financial conditions. To this end, an integrated techno-economic and environmental assessment framework was developed for six grid-connected hybrid configurations and applied to a residential case study in Fayoum, Egypt. The principal contribution of the work lies in combining NPC-based cost optimization with a comprehensive comparative evaluation based on LCOE, renewable fraction, operational CO_2 emissions, grid dependence, and reliability indicators across the candidate system configurations. Among the six configurations examined, the Grid/PV/Battery system was identified as the most favorable option, achieving the lowest NPC and LCOE, the highest renewable fraction, the lowest operational CO_2 emissions, and zero unmet load under the modeled grid outage conditions. The findings indicate that higher initial investment in PV generation and battery storage can be economically justified through substantial reductions in long-term operating cost and dependence on purchased grid electricity. In contrast, lower capital alternatives with greater reliance on-grid supply or diesel backup were found to perform less favorably over the project lifetime.

An important insight of the study is that residential hybrid system selection should not be based solely on initial capital cost. The sensitivity analysis showed that the preferred configuration is influenced more strongly by the nominal discount rate and inflation rate than by diesel fuel price, indicating that macro-financial conditions are the dominant drivers of long-term economic performance under the adopted assumptions. Additional sensitivity results showed that the preferred configuration is robust across the examined financing conditions, whereas its sensitivity to the PV derating factor is more pronounced. Specifically, the Grid/PV/Battery system remains optimal at higher derating levels of 70% and 80%, while the optimal solution shifts to the Grid/Diesel configuration at lower derating levels of 50% and 60%.

It should be emphasized, however, that the superiority of the Grid/PV/Battery configuration is established within the specific assumptions adopted for the Fayoum case study. Accordingly, the reported result should be interpreted as a case-specific finding within a transparent and reproducible modeling framework, rather than as a universally generalizable conclusion for all residential settings.

The study also has several limitations. The analysis assumes a fixed long-term load profile, simplifies the treatment of PV degradation, considers only one battery chemistry, restricts the environmental evaluation to operational CO_2 emissions, and adopts a random outage representation rather than alternative peak period or seasonally clustered outage scenarios. Future research should therefore extend the framework by incorporating load growth, explicit PV aging, battery technology comparison, life cycle environmental assessment, and scenario-based outage modeling. Within these bounds, the proposed framework provides a robust methodological basis for evaluating residential hybrid energy systems under financial, technical, and reliability constraints.

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Nomenclature

Symbol	Description	Unit
NPC	Net Present Cost	USD
LCOE	Levelized Cost of Energy	USD/kWh
C_{cap}	Capital cost of system components	USD
$C_{op}(t)$	Operation and maintenance cost in year t	USD/year
$Cfuel(t)$	Diesel fuel cost in year t	USD/year
$RC(t)$	Replacement cost	USD
$RV(t)$	Revenue over the project lifetime	USD
d	Nominal discount rate	%
f	Inflation rate	%
T	Total project lifetime	year
t	Year step	year
$load_{unmet}$	Unmet load ratio	%
$E_{unserved}(h)$	Unserved electrical energy at hour h	kWh
$E_{load}(h)$	Electrical load demand at hour h	kWh
h	Hourly time step index	h
P_{pv}	Installed PV capacity	kW
P_{DG}	Installed diesel generator capacity	kW
SoC	Battery state of charge	%
RF	Renewable fraction	%

Abbreviations

Abbreviation	Definition
CAPEX	Capital expenditure
CO_2	Carbon dioxide
DC	Direct current
DG	Diesel generator
GHG	Greenhouse gas
GHI	Global horizontal irradiance
HOMER Pro	Hybrid Optimization of Multiple Energy Resources Professional
yr	Year
W	Watt
kW	Kilowatt
kWh	Kilowatt hour
O&M	Operation and maintenance
OPEX	Operating expenditure
PV	Photovoltaic
SoC	State of charge
TOU	Time of use
HRES	Hybrid Renewable Energy System

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