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Optimizing Cost and Performance of Hybrid Photovoltaic-Diesel Systems for Off-Grid Energy Solutions

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Abstract: Providing reliable electricity to remote or isolated communities is a major challenge, especially with traditional power grids that require expensive infrastructure and ongoing maintenance. Hybrid energy systems are becoming an increasingly attractive solution due to their flexibility, reliability, and lower long-term costs. This study explores a hybrid energy setup that combines solar photovoltaic panels, a Diesel generator, and battery storage, using HOMER software to analyze different configurations. The goal is to find the most cost-effective setup that still ensures a steady and reliable energy supply. Several scenarios are simulated, taking into account local solar resources, changes in fuel prices, and varying electricity demand. The findings show that hybrid systems can significantly cut Diesel use, improve energy efficiency, and offer a cleaner, more sustainable energy solution for off-grid areas. Overall, the proposed system proves to be a practical and affordable alternative for communities that are hard to reach with traditional power infrastructure.

Keywords: Hybrid system, Photovoltaic-Diesel system, Techno-economic optimization, Off-grid energy, HOMER software.

Introduction

Providing reliable electricity to remote or isolated communities remains a significant global challenge, especially in developing countries where grid extension is economically unfeasible due to high investment, infrastructure, and maintenance costs (Mohammed et al., 2014; Come Zebra et al., 2021). In many off-grid regions, diesel generators are still the primary power source. However, they are associated with high operating costs, dependence on fluctuating fuel prices, limited reliability, and considerable greenhouse gas emissions (Karakoulidis et al., 2011; López-Castrillón et al 2021). To overcome these challenges, hybrid renewable energy systems (HRES) — combining photovoltaic (PV) panels, diesel generators, and battery storage — have become a promising alternative for decentralized electrification. Such systems can enhance reliability, reduce diesel fuel consumption, and lower the long-term cost of energy while minimizing environmental impact (Aziz et al., 2022; Almashakbeh et al., 2023). The integration of renewable sources with diesel backup provides flexibility in meeting variable loads, particularly in regions with intermittent solar radiation (Seiyefa et al., 2024) .

Several techno-economic assessments have been carried out to evaluate the feasibility of PV–diesel–battery systems in different geographical contexts. For instance, Jahed et al. (2024) performed a comparative analysis using various battery technologies — including lithium-ion and vanadium redox — and found that the choice of storage has a strong influence on system cost and performance. Similarly, Wang et al. (2025) demonstrated through HOMER simulations that PV–diesel–battery configurations can significantly reduce operational costs and improve sustainability in agricultural and rural applications. In addition, research has shown that these systems are sensitive to parameters such as fuel price fluctuations, solar resource availability, and variations in load demand (Omar et al., 2025). Come Zebra et al. (2021) emphasized that hybrid systems can provide a reliable and clean energy supply when properly optimized, considering local climatic and economic conditions. Advanced simulation and optimization tools such as HOMER, RETScreen, and MATLAB-based algorithms have been widely used to determine the most cost-effective and technically viable configurations (Ram et al., 2022).

Beyond techno-economic considerations, hybrid systems also play a crucial role in achieving sustainable development goals (SDG 7) by promoting access to affordable, reliable, and modern energy in rural and isolated communities (Off-Grid Hybrid Electrical Generation Systems, 2024). They contribute to energy security and resilience, especially in developing nations where energy access remains uneven (Mohammed et al., 2014; Come Zebra et al..2021). Despite the growing body of literature, several research gaps persist. Many studies rely on generalized meteorological or load data rather than site-specific inputs. Furthermore, comprehensive sensitivity analyses addressing the combined effects of fuel price variation, component degradation, and renewable fraction optimization are still limited (Aziz et al., 2022; Almashakbeh et al., 2023).Therefore, further investigation is needed to determine the optimal hybrid configuration under varying technical and economic conditions.

In this context, the present study aims to determine the optimal configuration of a hybrid PV–diesel–battery system for off-grid electrification using HOMER software. The objective is to minimize the Net Present Cost (NPC) and Levelized Cost of Energy (LCOE) while ensuring high reliability and sustainability. Several scenarios are simulated to evaluate the impact of local solar resources, diesel price variations, and changing load profiles. The findings contribute to developing practical and economically viable off-grid solutions for remote communities.

Presentation of the Hybrid System

The hybrid energy system is mainly composed of photovoltaic (PV) units for power generation, supported by a diesel generator as a complementary fossil-based source. The system design is optimized according to the month with the highest solar irradiation to ensure maximum use of the available solar potential. During months with reduced solar energy, the diesel generator operates to compensate for the energy shortfall. The overall configuration of the Photovoltaic–Diesel–Battery hybrid system is illustrated in Figure 1.

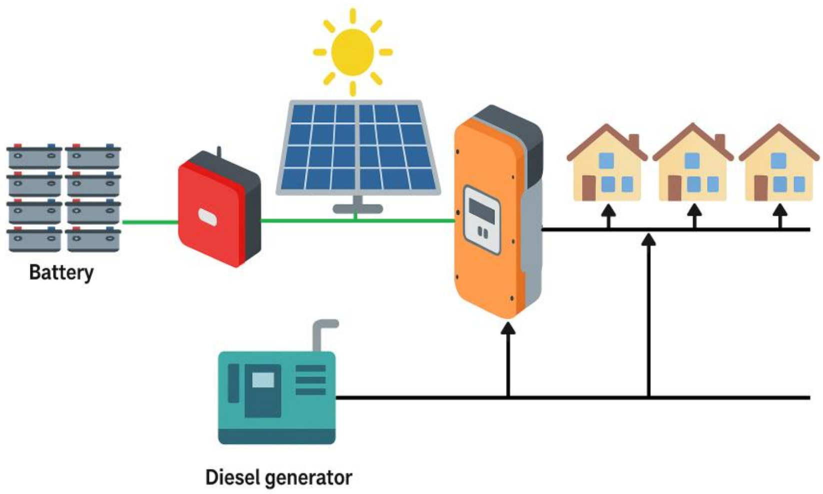


Figure 1. Configuration of the studied hybrid system

Sizing and Simulation Methodology

The general approach used for system sizing and simulations is summarized in the following steps:

1. Assessment of the energy demand (electricity consumption);
2. Preliminary manual sizing of the main system components.
3. Identification of the required equipment (solar panels, converter, and batteries) in the HOMER software environment.
4. Input of necessary data into HOMER, including:
   a). Energy consumption profile;
   b). Solar resource data for the selected location;
   c). Equipment specifications (capital cost, operation, and maintenance costs);
5. Execution of simulations using HOMER.
6. Iterative optimization of HOMER results to achieve the most cost-effective and technically optimal configuration;
7. Sensitivity analysis, if required, to assess system performance under varying parameters;
8. Validation of the system configuration based on simulation outcomes.

Solar Potential of the Selected Location

The selected site is an isolated area located in the Wilaya of Sidi Bel Abbès, Algeria. The average daily solar irradiation for each month of the year is presented in Table 1. It should be noted that the solar resource data can be obtained directly in HOMER software by clicking on the *"Get Data Via Internet"* icon.

Table 1. Solar radiation data of the selected location

Month	Irradiation (kWh/m^2/j)
January	2.76
February	3.72
March	4.68
April	5.78
May	6.63
June	7.22
July	7.26
August	6.31
September	5.08
October	3.9
November	2.85
December	2.45

Figure 2 presents the monthly solar radiation of the study site located in the wilaya of Sidi Bel Abbès, along with the monthly evaluation of solar irradiation shown in yellow and the illumination factor shown in red.

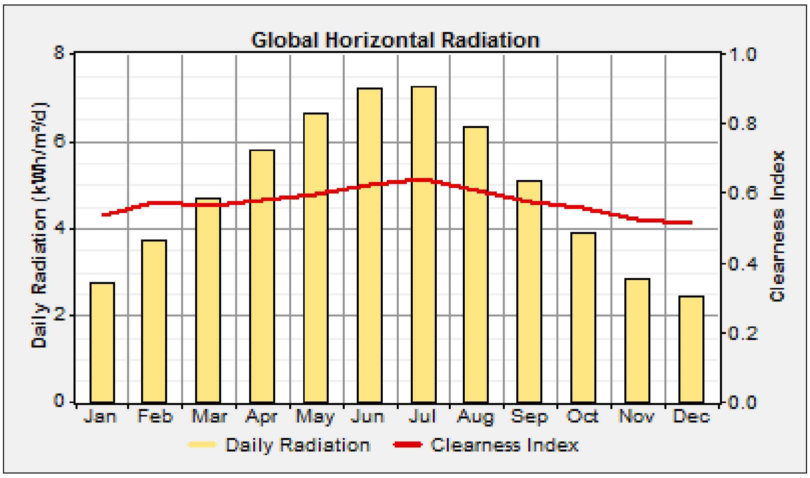


Figure 2. Monthly solar irradiation of the study region in the wilaya of Sidi Bel Abbes.

Load Profile

The estimated load profile plays a crucial role in choosing a suitable power supply system for a remote household or village. Since electricity consumption in a household fluctuates over the year, the demand is not uniform. Seasonal changes, particularly variations in daylight hours, lead to shifts in peak load times throughout the year. Figure 3 shows the daily load profile, where energy consumption remains low during nighttime hours (between midnight and 6 a.m.), while higher consumption is observed between 7 a.m. and 12 p.m., 2 p.m. and 5 p.m., and again from 7 p.m. to 10 p.m.

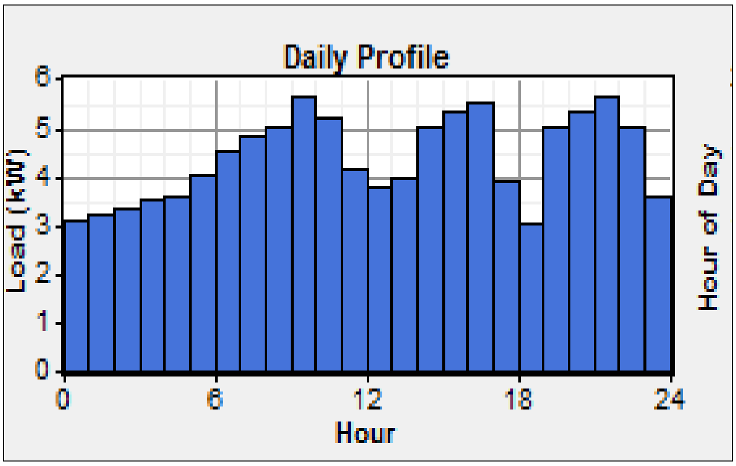


Figure 3. Daily load profile

Construction of the Hybrid System

Figure 4 shows the architecture of the Photovoltaic–Diesel hybrid system designed using the HOMER software.

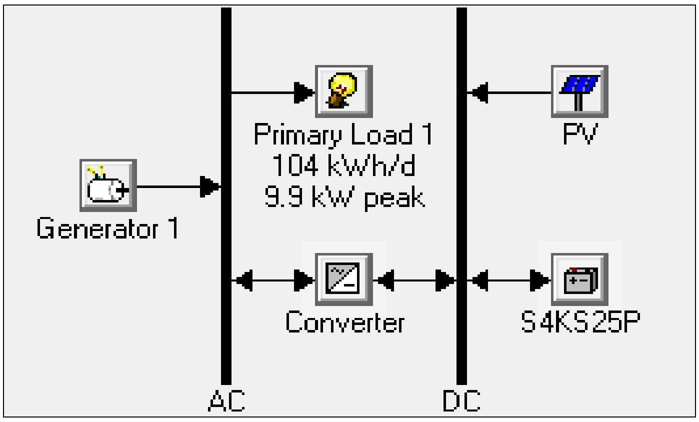
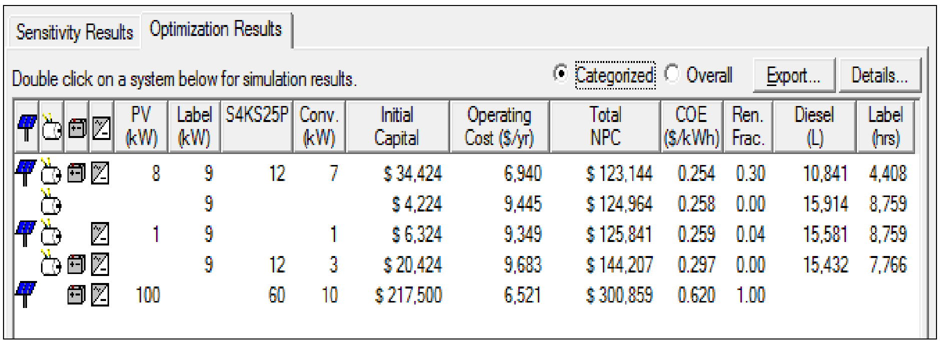


Figure 4. Configuration of the Photovoltaic–Diesel hybrid system modeled using HOMER

Simulation Results



	PV (kW)	Label (kW)	S4KS25P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
	8	9	12	7	$ 34,424	6,940	$ 123,144	0.254	0.30	10,841	4,408
		9			$ 4,224	9,445	$ 124,964	0.258	0.00	15,914	8,759
	1	9		1	$ 6,324	9,349	$ 125,841	0.259	0.04	15,581	8,759
		9	12	3	$ 20,424	9,683	$ 144,207	0.297	0.00	15,432	7,766
	100		60	10	$ 217,500	6,521	$ 300,859	0.620	1.00		

Figure 5. Simulation results.

After running the simulation, HOMER displays the solutions in a list format, ranked according to the lowest cost of energy. The configurations are ordered from the most cost-effective to the least economical based on the Net Present Cost (NPC), as shown in Figure 5 and Table 2 below. Based on the obtained results, the first configuration represents the best energy installation — it is the optimal solution proposed by the HOMER software, with a Net Present Cost (NPC) of 123.144 $.

Table 2. Net present cost "NPC" ($).

Configurations	Net Present Cost "NPC" ($).
PV+Diesel+ Battery + Converter	123.144
Diesel	124.964
PV+Diesel+Converter	125.841
Diesel+Battery+Converter	144.207
PV+Battery+Converter	300.859

Conclusion

The proposed hybrid Photovoltaic–Diesel–Battery system designed for the studied region of Sidi Bel Abbès (Algeria) represents a reliable, versatile, and sustainable energy solution for off-grid power supply. It effectively combines the advantages of renewable resources—particularly the abundant local solar potential—with the flexibility and immediate availability of diesel generation when required. This configuration ensures continuous power availability, enhances overall energy efficiency, and significantly reduces both operating costs and carbon emissions, contributing to a cleaner and more autonomous energy transition for remote communities.

Recommendations

It is recommended to conduct future studies that integrate other renewable energy sources, such as wind or biomass, along with advanced control strategies to further enhance the system's energy efficiency and sustainability.

Scientific Ethics Declaration

* The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

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