

Enhancing Rural Electrification in Mauritania through Hybrid Energy Solutions: A Techno-Economic Analysis Using HOMER Software

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Abstract

The African continent remains the least electrified, particularly acute in sub-Saharan Africa, where there is a significant gap between urban and rural electrification rates. To address the electricity access gap in isolated rural areas, decentralized electricity production solutions, such as hybrid systems (HS) that combine diesel generators, solar photovoltaics (PV), and batteries, are increasingly being proposed. The present study examines the optimal combination of these hybrid energy sources for three villages across different climatic regions in Mauritania. Using a MATLAB scripts to analyze the load profiles of the selected villages and HOMER (Hybrid Optimization Multiple Energy Resource) software for techno-economic analysis, this research identifies the best hybrid system configurations based on the leveled cost of energy (LCOE) and net present cost (NPC). The results provide a comprehensive analysis of generation plant hybridization options, allowing to reduce the energy cost of a kWh to approximately \$0.3, approximately half of the current cost of electricity production in isolated areas (26.36 MRU/kWh, equivalent to \$0.66/kWh). In addition, this work offers valuable data to support the Mauritanian government's rural electrification initiatives.

Keywords

Hybrid System, Rural Electrification, Homer Energy Tool, LCOE, NPC

1. Introduction

Access to clean and affordable energy is among the most important sustainable development goals established by the United Nations, which are to eradicate poverty, protect the planet, and guarantee prosperity for all by 2030 [1]-[4]. Nowadays, the big challenge is to reduce the wide gap between urban and rural electrification rates, particularly in sub-Saharan Africa [5] [6]. In Mauritania, 90% of urban areas have access to electricity in 2022, whereas in rural areas, the access rate drops to just around 6% [7] [8]. To address the issue of electricity access in isolated rural areas, decentralized electricity production solutions are available [9]-[12]. These off-grid solutions enable independent electricity generation.

Mauritania, located between the 15th and 27th parallels north, spans an area of 1,030,700 km², including a maritime coastline of approximately 700 km [13] [14]. The country experiences a generally hot and dry climate, with a Saharan climate in the north and a Sahelian climate in the south. The climate is milder along the Atlantic coast. Temperatures vary significantly, with maximums ranging between 44°C and 47°C in May and June, and minimums dropping to between 10°C and 19°C in January and February. Consequently, Mauritania can be divided into three major agro-ecological zones: the extremely dry Saharan desert in the north, the Sahel in the south with higher precipitation, and the Sudan Savannah along the Senegal River, which forms the border with Senegal, as illustrated in **Figure 1** [15]. The population of Mauritania was estimated to exceed 4.9 million in 2023, with an annual demographic growth rate of 2.8%. A significant portion of the population (51%) lives in rural areas [16]. The national grid is seldom extended to remote rural areas, leaving these regions isolated from any form of modern energy. A variety of mini-grid development approaches are available today for rural electrification. These approaches can be classified based on the technologies used and the institutional and financial arrangements. Mini-grids can employ single-generation technologies, such as diesel generators, solar photovoltaic systems, wind turbines, or hydropower, or they can be hybrid systems that combine two or more technologies. Ownership and management of mini-grids can belong to the state, private sector, or local communities [17].



Figure 1. Sites location.

In Mauritania, the public electricity service in rural areas is regulated by the Regulatory Authority (ARE) through Public Electricity Service Delegation (DSPE) licenses. According to the DSPE's 2022 results, 15 isolated power plants serving 26 rural localities (with 6,926 electricity service subscribers) produced a total of 4.4 MWh of energy, with 1% of this coming from solar sources [18]. To illustrate the different types of electrical consumers in Mauritania, **Figure 2** displays the distribution of subscribers by energy consumption category in rural areas. Notably, 61% of subscribers have a monthly consumption of 25 kWh or less, largely due to the higher tariff rates compared to those in urban areas. Currently, the cost of electricity sold in rural areas is 26.36 MRU per kWh, equivalent to \$0.66 [18] [19]. Mauritania benefits from exceptional renewable energy resources thanks to its unique geographical position and favorable climatic conditions [20] [21]. In this context, the use of hybrid systems (HS) for rural electrification is one of the most proposed solutions [22]-[25]. These systems are designed to deliver a sustainable energy supply, lower electricity costs for rural communities, and improve the efficiency and long-term viability of off-grid rural electrification operations.

This paper examines the optimal combination of different hybrid energy sources for three villages across various climate regions in Mauritania. The proposed system includes a diesel generator, solar photovoltaic (PV) panels, and batteries. For each of the three selected sites, the system components will be integrated to form the basic hybrid system. Load profiles were measured and plotted using Matlab scripts for these villages. Techno-economic analysis was performed with HOMER (Hybrid Optimization of Multiple Energy Resources) software to identify the best hybrid system solution based on the levelized cost of energy (LCOE) and Net Present Cost (NPC). The goal of this study is to provide detailed analysis and data on hybrid generation plant options, enabling the Mauritanian government to make informed decisions to meet its rural electrification objectives.

VARIOUS ENERGY CONSUMERS TYPES

- Category 1 (Energy consumed/month \leq 25 kWh)
- Category 2 (25 kWh < Energy consumed/month \leq 120 kWh)
- Category 3 (Energy consumed/month > 120 kWh)

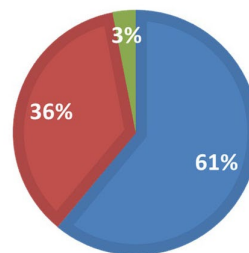


Figure 2. Energy consumer categories in Mauritania.

2. Configuration and Modeling of Proposed Hybrid Systems

Modeling is a crucial step prior to the optimal sizing phase. This paper proposes a generalized configuration of a Hybrid System (HS), as illustrated in **Figure 3**. The configuration includes various combinations of photovoltaic generators, diesel generators (DG), and a battery bank. Due to the intermittent nature of renewable energy systems, DGs and battery banks are used as backup resources. The paper describes a mathematical model for each component and provides key equations to determine HOMER outputs, including the levelized cost of energy (LCOE), Net Present Cost (NPC), and the Economic Distance Limit (EDL) from the grid.

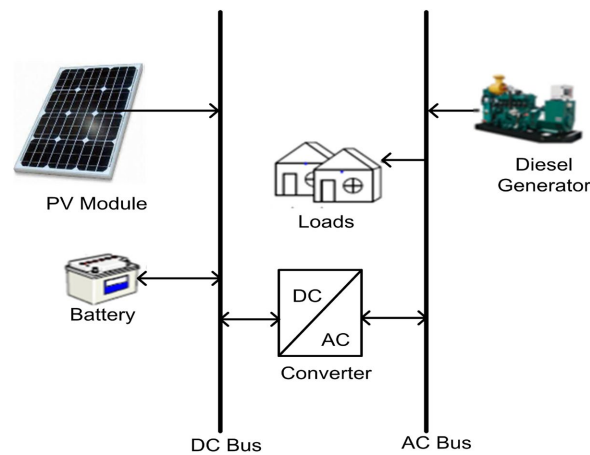


Figure 3. Proposed hybrid system configuration.

2.1. Model of PV Generator

For the three selected villages, solar irradiation data was sourced from the NASA Surface Meteorology and Solar Energy database, covering a 22-year period from July 1983 to June 2005 [26]. The data shows that solar radiation is available nearly throughout the year, as shown in **Figure 4**, with an annual average of 4.75 kWh/m²/day. The lowest solar radiation occurs in January and December, while the highest levels are observed in April and June.

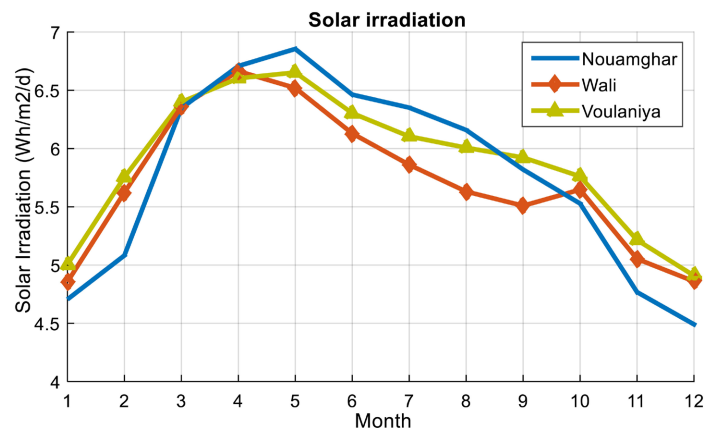


Figure 4. Daily average monthly solar irradiation.

Based on the area of the photovoltaic modules (A_{pv}) and the solar radiation (I_r) the photovoltaic output power (P_{pv}) can be determined as the following equation [27] [28]:

$$P_{pv} = A_{pv} * \eta_{pv} * I_r \quad (1)$$

With: η_{pv} : overall efficiency of the module, it is given by:

$$\eta_{pv} = \eta_r * \eta_{pc} * [1 - \beta_t (T_c - T_{NOCT})] \quad (2)$$

η_r : reference efficiency of the photovoltaic module. It depends on the technology used. η_{pc} is the degradation factor. Here, η_{pc} will be equal to 0.9. β_t is the coefficient of the influence of the temperature of the photovoltaic. T_c is the cell temperature (°C). TNOCT is the optimal operating Cell Temperature.

2.2. Diesel Generator

The diesel generator (DG) is crucial for maintaining the stability of the hybrid system. However, its efficiency decreases significantly as the load demand reduces. Consequently, fuel consumption becomes a major factor, making the operating cost a significant consideration. The fuel consumption of the generator Q as a function of its electrical power is given as follows [29] [30]:

$$Q = F_0 * P + F_1 * P_{gen} \quad (3)$$

where P is the generated power, P_{gen} [kW] is the rated power, F_0 (L/hr) and F_1 (Lhr/kWrate) are coefficients of the fuel consumption parameters. These coefficients can be obtained from the technical sheet of the selected diesel generator model when it operates at 50% and 100% of its nominal load.

2.3. Model of Battery Bank

To store the excess energy product by intermittent RE and to control the charge process, the battery capacity is determined as following equation [30]:

$$C_{bat} = \frac{E_L * AD}{\eta_{inv} * \eta_{bat} * DOD} \quad (4)$$

Where E_L is the load demanded, AD is autonomy days, η_{inv} is converter efficiency, η_{bat} is battery efficiency and DOD is depth of discharge (80%).

3. Economic Performance

To compare the electrification solutions for the selected villages, the primary criterion will be the cost of these projects. Given the variability in investment and maintenance costs, it is crucial to evaluate them on a common basis. In the context of electrification projects, commonly used indicators include:

Levelized Cost of Electricity (LCOE): Measures the average cost per unit of electricity produced over the system's lifetime.

Net Present Cost (NPC): Represents the total cost of the project, discounted to present value.

Renewable Energy Fraction (REF): The proportion of energy generated from

renewable sources.

Load Factor (LF): Reflects the performance of the system in meeting the consumer's load demand pattern.

3.1. Levelized Cost of Electricity

The levelized cost of electricity (LCOE) is a key indicator for determining the price at which electricity must be sold to break even over the project's lifetime. It accounts for all costs associated with electricity production, including investment, operation, maintenance, and fuel costs. The LCOE is calculated using the following equation [31]:

$$LCOE = \frac{\sum_{t=1}^N \left(\frac{I_t + M_t + F_t}{(1+r)^t} \right)}{\sum_{t=1}^N \left(\frac{E_t}{(1+r)^t} \right)} \quad (5)$$

Where:

N = Project lifetime.

I_t = Investment costs in year t [US\$].

M_t = Maintenance costs in year t [US\$].

F_t = Fuel costs in year t [US\$].

E_t = Annual Energy delivered by the system in year t [kWh].

r = discount or rate of return [%].

3.2. Net Present Cost

In order to estimate the necessary financing, the total Net Present Cost (NPC) of a system is determined by equation (6). The NPC is the present values of all components that include essentially the capital costs and O&M over the lifetime of project [32].

$$NPC = \sum_{t=1}^N \left(\frac{C_t}{(1+r)^t} \right) \quad (6)$$

Where: $C_t = R_t - M_t - F_t - I_t$ the net cash-flow for period (t), i.e. revenue R_t minus expenses.

A discount rate (of 10% is recommended for projects of this type in sub-Saharan Africa [33]).

3.3. Renewable Energy Fraction

The Renewable energy fraction (REF) is the proportion of total energy generated by renewable energy sources in system and is determined as follows:

$$REF = \left(1 - \frac{\sum P_{DG}}{\sum P_{RE}} \right) * 100 \quad (7)$$

Where PDG is the diesel generator output power and PRE is the power from renewable energy sources.

3.4. The Load Factor

The Load Factor (LF) is determined as ratio of the average load power to the peak load, as given in equation (8):

$$LF = \left(\frac{L_{average}}{L_{peak}} \right) \quad (8)$$

Where $L_{average}$ and L_{peak} are average load demand and peak load demand, respectively.

3.5. Economic Distance Limit

The Economic Distance Limit (EDL) corresponding to the distance from grid where the NPC of the extending grid equal to the NPC of the stand-alone system. The EDL can be calculated on HOMER using follows equation [32]:

$$D_{grid} = \frac{(C_{NPC} * CRF(i, R_{proj})) - C_{power} * L_{tot}}{C_{cap} * CRF(i, R_{proj}) + C_{om}} \quad (9)$$

Where: CNPC is the Total Net Present Cost, CRF is the Capital Recovery Factor, i is the Interest rate (%), R_{proj} is the Project life time in years, C_{power} is the Cost of power from the grid in (\$/kWh), L_{tot} is the Total primary and deferrable load in (kWh/year). C_{cap} is the Capital cost of grid extension in (\$/km), C_{om} is the O&M cost of grid extension in (\$/year/km).

4. Results and Discussion

4.1. HOMER Simulation Tool

In order to analyze and design the proposed hybrid system, HOMER (Hybrid Optimization Model for Electric Renewable) simulation tool have been used. HOMER software is one of the major global standards in the field of microgrid optimization in all sectors, from electrification of decentralized villages to large structures connected to the network. It integrates powerful tools for simulating and optimizing technical-economic analyses [34] [35]. The HOMER algorithm selected the best system configurations based on the lowest NPC (Net Present Cost). **Figure 5** illustrates the block diagram and principle operating of the Homer software. Also, the costs and simulation parameters of hybrid system for this study electrification are summarized in **Table 1**. The Diesel generator is already on site in this case study, the economic calculation will therefore be free of its capital cost. This being in any case low compared to its operating cost, this will have little influence on the results due to actual price of the fuel in Mauritania (1.3 \$/L) [36].

Table 1. Key parameters for Homer simulation.

Component	Cost	Value	Remarks/source
Diesel generator	Capital	0 USD/kW	Averages data deduced from similar recent studies in Mauritania by [37]
	Replacement	290 USD/kW	

Continued

	O\$M	0.35 USD/op.hr	
Diesel generator	Fuel	1.242 USD/L	In Mauritania, actual price of the diesel at the time of study was 1.3 USD/L [36]. Nevertheless, an extra (10 %) was added for transportation and delivery costs.
	Capital	1200 USD/kW	
	Replacement	1200 USD/kW	Averages data deduced from similar recent studies in Mauritania by [37]
Solar PV pannel	O\$M	24 USD/kW/yr	
	Tilt angle	18°	The typical optimal values for Mauritania are within 12° to 18°
	Derating factor	80%	
	Capital	300 USD/kWh	
Battery	Replacement	300 USD/kWh	Averages data deduced from similar recent studies in Mauritania by [37]
	O\$M	6 USD/kWh	
	Capital	300 USD/kW	
Convertisseur	Replacement	300 USD/kW	Averages data deduced from similar recent studies in Mauritania by [37]
	O\$M	6 USD/kWh	
	Project lifetime	25 years	In the literature, the typical lifespan for similar projects
Economics	Discount rate	10%	
	Inflation	10%	From [33], [35]

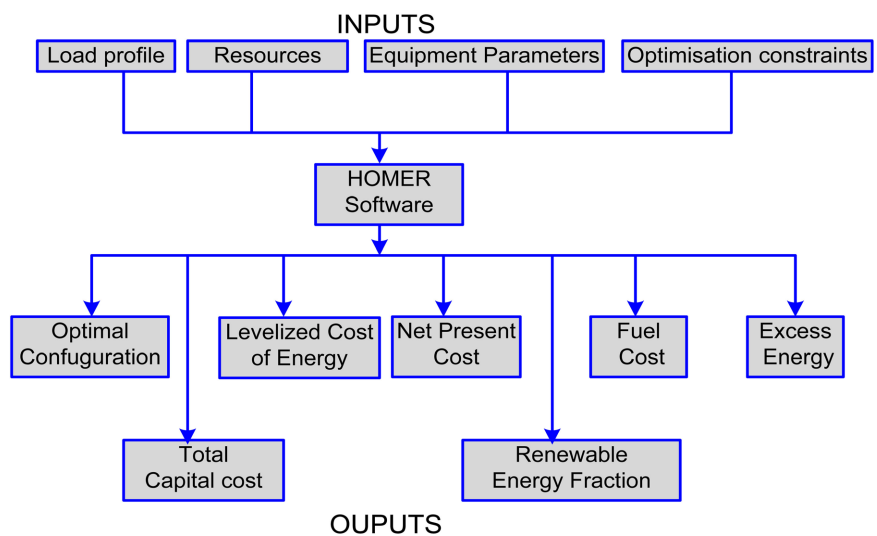


Figure 5. HOMER Architecture with principal operation.

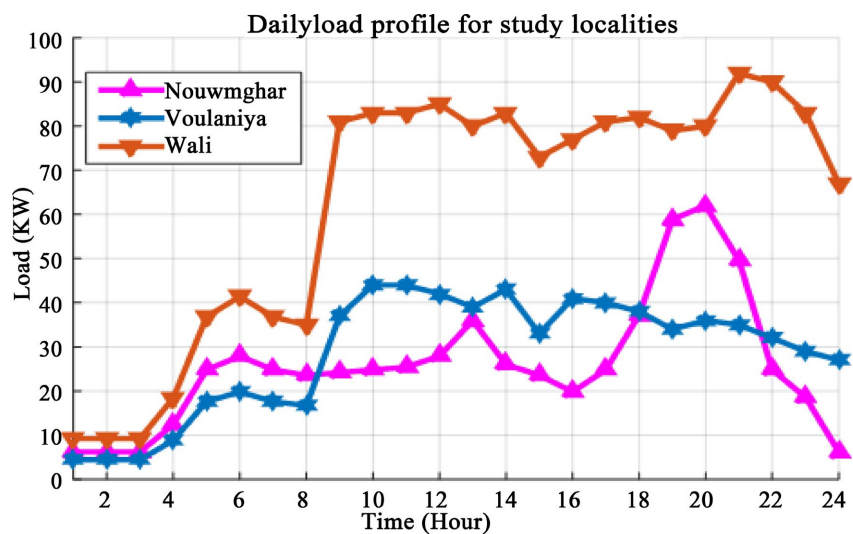
4.2. Comparative Simulation Results

4.2.1. Energy Demand and Load Factor

The simulation results for the hybrid PV/ Diesel Generator/ Battery systems across the three villages—Voulaniya, Wali, and Nouawmghar—reveal key insights into their respective energy needs, costs, and system performance. According to the National Statistics Agency (ANSADE) in 2023, the total population of the Voulaniya amounts to 3339 inhabitants, the Wali about 8406 inhabitants, and 690 inhabitants in Nouamghar (ANSADE. 2024). The load profile for each community was obtained from the consumption data of the diesel generator installed on-site, as illustrated in **Figure 6**. These load consumption are used to assess the performance of proposed PV/diesel/battery system.



(a)



(b)

Figure 6. Daily load profiles: (a) a photograph of one of Generator's present on Site, (b): load profile curves.

Table 2 presents the Daily Energy Demanded and Load Factor for each measures load profiles. It can observe that Voulaniya has a relatively lower peak load and daily energy demand compared to Wali and Nouawmghar, resulting in a higher load factor. This indicates a more stable and predictable energy consumption pattern. For Wali exhibits the highest peak load and daily energy demand, with a lower load factor. This suggests significant variability and higher energy needs. Nouawmghar has moderate peak load and energy demand, with the lowest load factor, indicating more variability in energy usage.

Table 2. Study cases of load factor.

Village	Peak Load (kW)	Daily Energy Demand (kWh/day)	Load Factor
Voulaniya	44	687.72	0.65
Wali	92	1495.00	0.46
Nouawmghar	62	621.86	0.42

4.2.2. System Components and Performance

Figure 7. shows the HOMER Schematic of the proposed system. The obtained optimal components resultants for each case are shown in **Table 3**. Voulaniya has the smallest PV generator size and battery capacity but maintains a reasonable renewable energy fraction. It also has the highest excess electricity percentage, indicating potential overproduction. Wali features the largest PV generator and battery capacity, with a higher renewable energy fraction but also a lower excess electricity percentage. This indicates a more balanced integration of renewables and demand. Nouawmghar has the smallest PV generator relative to its load but achieves the highest renewable energy fraction. Its excess electricity percentage is the lowest, suggesting optimal use of generated renewable energy.

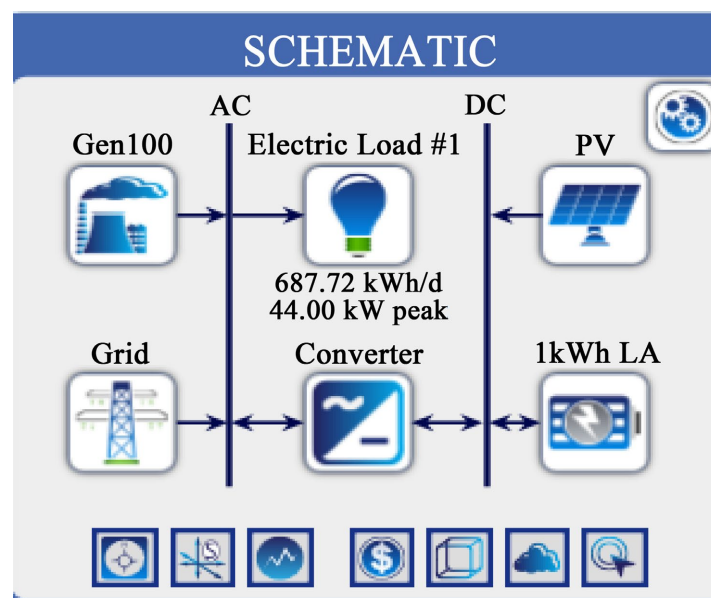


Figure 7. HOMER Schematic of the proposed system.

Table 3. Obtained optimal components for each case.

Village	PV Generator (kW)	Diesel Generator (kW)	Battery (Ah)	Converter (kW)	Electricity Production (MWh/yr)	Excess Electricity (%)
Voulaniya	136	100	232	48.9	349.38	23.3
Wali	272	100	496	94	715.03	19.2
Nouawmghar	121	100	440	40	296.13	16.0

4.2.3. Economic Analysis

It can be noted from **Table 4** that Voulaniya has the highest levelized cost of electricity and total net present cost, making it the most cost-effective option among the three villages. Its operating cost is moderate, with a relatively high fuel consumption and CO₂ emissions. Wali has the highest total net present cost but the lowest levelized cost of electricity. It also has the highest operating costs and CO₂ emissions, reflecting its higher diesel usage. For Nouawmghar shows a balance between cost and performance. While its levelized cost of electricity is higher, its total net present cost is similar to Voulaniya, and it has the lowest operating cost and CO₂ emissions.

Table 4. Economic results.

Village	Total Net Present Cost (\$)	Levelized Cost of Electricity (\$/kWh)	Operating Cost (\$)	Total Fuel Consumption (L/year)	CO ₂ Emissions (kg/year)	Optimal Hybrid System
Voulaniya	1,109,399	0.342	66,686	34,080	98,138	PV/DG/Battery
Wali	2,050,732	0.291	119,712	65,358	170,948	PV/DG/Battery
Nouawmghar	1,088,756	0.371	61,859.8	26,125	68,331	PV/DG/Battery

4.2.4. Economic Distance Limit

Table 5 represents the Breakeven Grid Extension Distance Economic. It can be noted that: Voulaniya has the shortest breakeven grid extension distance, indicating that extending the grid to this village is less economically favorable compared to installing a hybrid system due to its distance to the existing grid. Wali has the longest distance, making grid extension more viable in a distance less than 40 km. Nouawmghar falls in between, with a moderately favorable distance for grid extension relative to its hybrid system costs.

Table 5. Economic distance limit.

Village	Breakeven Grid Extension Distance (km)
Voulaniya	28.65
Wali	40.00
Nouawmghar	31.24

4.2.5. Overall Findings

- **Customized Solutions:** The results emphasize the necessity of tailoring hybrid system designs to each village's specific energy demands and load profiles. Voulaniya benefits from its stable load and lower costs, while Wali's high

demand and variability require more robust and flexible system designs.

- **Cost-Effectiveness:** Voulaniya's lower costs and higher excess electricity suggest it can achieve cost savings and operational efficiency with its current setup. In contrast, Wali's higher costs and emissions highlight the need for better integration of renewable sources or improved system management.
- **Future Considerations:** Ongoing monitoring and system adjustments based on real-time data and changing load patterns are essential to maintain optimal performance and cost-effectiveness. Enhanced focus on reducing CO₂ emissions and operational costs can further improve system sustainability.

4.2.6. Conclusion

This study evaluates the optimal hybrid energy solutions for rural electrification in Mauritania, focusing on a combination of diesel generators, solar photovoltaic (PV) panels, and batteries. By employing HOMER software for techno-economic analysis, the research provides a comprehensive assessment of system performance across three diverse villages—Voulaniya, Wali, and Nouawmghar.

4.2.7. Key Findings:

(1) System Configurations and Economic Viability:

- The hybrid systems, incorporating PV panels, diesel generators, and batteries, were found to be effective in meeting the energy demands of the selected villages. The configurations vary based on local load profiles and climate conditions, highlighting the need for customized solutions.
- Voulaniya benefits from a lower levelized cost of electricity (LCOE) and total net present cost (NPC), attributed to its stable load profile. Wali, with its high variability in energy demand, shows higher costs and CO₂ emissions, indicating the necessity for a more adaptable system. Nouawmghar presents a balanced scenario with moderate costs and renewable energy integration.

(2) Economic Distance Limit (EDL):

- The analysis confirms that extending the grid is economically less favorable compared to deploying hybrid systems in these villages. The EDL calculations demonstrate that hybrid solutions are more cost-effective for the rural areas studied, particularly those at a significant distance from existing grid infrastructure.

(3) System Design Considerations:

- **Load Profiles:** The stable demand in Voulaniya allows for reduced battery storage and diesel use, while the variable demand in Wali requires more extensive storage and flexible system configurations.
- **Cost Optimization:** Stable load profiles enable lower system costs, whereas variable loads necessitate increased investment in storage and generation capacity.
- **Renewable Energy Integration:** Villages with consistent energy needs can achieve higher renewable energy fractions, whereas those with fluctuating demands may rely more on diesel or require larger battery systems.

5. Conclusions and Recommendations:

The study highlights the importance of tailoring hybrid energy solutions to the specific needs and conditions of each village. Customization of system designs based on local load profiles and climatic conditions enhances cost-efficiency, improves renewable energy utilization, and ensures reliable power supply. The findings offer valuable insights for the Mauritanian government, aiding in the development of effective rural electrification strategies that balance economic feasibility with environmental sustainability. Future research should focus on real-time monitoring and adjustments to maintain optimal system performance and address evolving energy demands.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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