Engineering-Economic Comparison of Grid-Tied and Standalone Solar Energy Solutions for Sustainable Rural Electrification

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Abstract: Access to reliable electricity continues to be a significant challenge in many rural areas of developing countries. This study offers a detailed engineering-economic comparison between grid-tied and standalone solar energy systems, with a focus on sustainable rural electrification. By utilizing real-world load profiles, solar resource data, and system component costs, we assess both configurations based on performance indicators such as Levelized Cost of Energy (LCOE), Net Present Cost (NPC), system reliability, and environmental impact. A rural community scenario is modeled and simulated using HOMER Pro to evaluate system design under varying demand and climatic conditions. The results indicate that while grid-tied systems provide cost benefits in areas with stable grid access, standalone systems offer enhanced energy independence and resilience in remote or underserved locations. These findings provide valuable insights for policymakers, energy planners, and stakeholders seeking sustainable, context-specific electrification solutions in developing regions.

Keywords: *Electrification, Photovoltaics, Microgrids, Sustainability, Economics.*

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I. INTRODUCTION

Access to reliable and affordable electricity is a significant developmental challenge in many rural areas of developing countries. Despite global efforts to enhance electrification rates, millions—especially in sub-Saharan Africa—still lack consistent power access. In West Africa, rural communities are particularly affected, relying heavily on polluting and costly energy sources such as kerosene lamps, diesel generators, and firewood. This absence of modern energy services negatively impacts education, healthcare, food security, and local economic growth.

To address these issues, decentralized renewable energy systems have emerged as viable and sustainable alternatives to traditional grid expansion. Among the available technologies, solar photovoltaic (PV) systems stand out for their modularity, scalability, decreasing installation costs, and the region's abundant solar resources. A critical design consideration is whether to implement a grid-tied solar system, which connects to the utility grid, or a standalone (off-grid) system that operates independently with battery storage to ensure a continuous power supply.

Grid-tied systems are often more cost-effective in areas with stable grid infrastructure, facilitating energy exchange and net metering. Conversely, standalone systems are essential in remote or underserved regions where grid expansion is economically unfeasible or technically impractical. Each configuration presents distinct technical and economic trade-offs related to system reliability, capital investment, long-term operational costs, and environmental performance.

II. LITERATURE REVIEW

A. Rural Electrification in Developing Countries

Rural electrification is widely recognized as a key driver of socio-economic development, yet many areas in the Global South are experiencing slow progress. The International Energy Agency (IEA, 2023) reports that over 600 million people in sub-Saharan Africa lack access to electricity, with West Africa representing a significant portion of this number. In these regions, extending the central grid is often challenged by high capital costs, difficult terrain, and low population density. As a result, decentralized energy solutions, especially solar-based systems, are becoming increasingly popular due to their flexibility, scalability, and cost-effectiveness.

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B. Solar PV Systems for Rural Electrification

Solar photovoltaic (PV) systems stand out as one of the most promising renewable energy technologies for rural and peri-urban communities. Their modular design allows for deployment at various scales, ranging from individual household installations to community-based mini-grids. The World Bank and African Development Bank have backed numerous solar initiatives throughout West Africa, focusing on both individual homes and essential social infrastructure like clinics and schools. However, the effectiveness of these systems relies on selecting the right configuration—either grid-tied or standalone—to meet local needs and conditions.

C. Grid-Tied Solar Systems

Grid-tied systems connect to the national utility grid and often use net metering, enabling users to send excess electricity back to the grid. The advantages of these systems include:

- Reduced need for battery storage
- Lower initial investment (in certain situations)
- Increased efficiency due to continuous operation

However, grid-tied systems are only practical in areas with a reliable and accessible grid, which is not the case in many regions of West Africa. Research by Olatomiwa et al. (2021) and Adaramola et al. (2020) indicates that inconsistent grid supply can affect the performance and reliability of grid-tied solar PV installations in Nigeria and Ghana.

D. Standalone (Off-Grid) Solar Systems

Standalone systems function independently of the utility grid and rely primarily on battery energy storage for reliability, especially during non-sunny hours. These systems are vital for remote villages and off-grid communities. While they provide energy independence and resilience, they typically:

- Require higher upfront costs
- Depend on effective load management and battery lifecycle planning
- Incur long-term replacement and maintenance expenses

However, studies such as Sambo et al. (2019) and Mensah & Antwi (2022) demonstrate that well-designed standalone solar systems can effectively meet the energy needs of households and small enterprises in rural West Africa, particularly where grid expansion is not an option.

Several comparative studies have been conducted to assess the techno-economic performance of grid-tied versus standalone systems. For example, Abdul-Wahab et al. (2020) utilized simulation tools like HOMER Pro to analyze both systems in rural Burkina Faso. Their findings indicated that grid-tied systems generally had a lower LCOE in areas with reliable grid access, while standalone systems were more effective in off-grid scenarios due to their enhanced autonomy. Similarly, Eleri et al. (2021) pointed out that hybrid standalone systems (solar + battery + generator) could outperform grid-tied systems in regions with inadequate utility services.

However, many of these studies have certain limitations, such as:

- Focusing on isolated case studies that lack broader applicability,
- Relying on outdated cost assumptions, or
- Not capturing region-specific data (like solar irradiance, load behavior, and policy factors) relevant to West Africa.

E. Justification for Current Study

Despite the growing interest in renewable electrification, there is still a lack of a clear, data-driven comparison of grid-tied and standalone solar PV systems tailored to rural contexts in West Africa. This study aims to bridge that gap by integrating engineering design parameters, cost structures, and system performance data to provide a well-rounded assessment of both types of systems. Through simulation-based modeling and analysis, it intends to support informed energy planning and policy development for sustainable rural electrification throughout West Africa.

III. METHODOLOGY

This section outlines the methodological framework used to compare grid-tied and standalone solar energy systems for rural electrification in West Africa. The analysis employs simulation-based modeling with HOMER Pro software, which is recognized for its effectiveness in designing and optimizing hybrid renewable energy systems. The methodology incorporates technical parameters, economic assumptions, and location-specific data to evaluate system performance and cost-effectiveness under realistic conditions.

A. Research Framework and Approach

The study follows a structured, simulation-based approach that includes the following steps:

- Selection of target location (a rural West African region with limited or unreliable grid access).
- Estimation of load demand based on typical consumption patterns of rural households.
- Acquisition of solar resource data for the selected location.
- Definition of system components and configuration parameters.
- Simulation of both grid-tied and standalone systems using HOMER Pro.
- Comparison using key technical and economic performance indicators.

B. Load Profile Estimation

A typical rural household energy demand scenario was created, assuming basic domestic appliances (lighting, fan, TV, phone charging, refrigerator). The daily energy demand was estimated at **2.6 kWh/day**, with a peak load of approximately **800 W**. For broader community

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electrification, a cluster of **5 to 10 households** is modeled, scaling the load proportionally.

- ***Load Growth Rate:*** 2% annually

C. Solar Resource and Climate Data

*T*he equations are an exception to the prescribed. Hourly solar irradiance data was obtained for a representative West African location (e.g., latitude ~7°–10°N), using NASA's Surface Meteorology and Solar Energy (SSE) database. The **average daily solar radiation** was set at **5.2 kWh/m²/day**, a typical value for regions like Nigeria, Ghana, and Burkina Faso.

D. System Configurations

- *Grid-Tied PV System*

- PV array (0.7 – 2.5 kW)
- Inverter (matched to PV size)
- Grid connection with tariffs and outage profile
- No battery storage
- Net metering enabled (optional sensitivity case)

- *Standalone PV System*

- PV array (1 – 3 kW, oversized to account for autonomy)
- Inverter
- Battery bank (e.g., Lithium-ion, 48V system)
- Charge controller (MPPT)
- Optional backup generator for reliability (used in sensitivity analysis)

E. Economic Assumptions

Table 1 Economic Assumptions

Parameter	Value
Discount rate	7%
Project lifetime	25 years
Inflation rate	2.5%
Grid electricity cost	₦60/kWh (or $0.08/kWh)
Diesel price	₦750/litre
Battery replacement interval	10 years
PV degradation	0.5% per year

Capital, replacement, and O&M costs were based on current market prices in West Africa, validated through literature and local supplier references.

F. Evaluation Metrics

The following metrics were used to assess and compare the two system types:

- *Net Present Cost (NPC):*

$$NPC = \frac{C_{ann}}{CFR_{(i,N)}}$$

- *Levelized Cost of Energy (LCOE):*

$$\text{LCOE} = \frac{\text{Total Anualized Cost}}{\text{Total Annual Energy Load Served}}$$

- **Renewable Fraction (%):** Share of energy supplied by PV
- **Unmet Load (%):** Indicator of system reliability
- **Excess Electricity (%):** Wasted energy due to overgeneration
- **CO_2 Emissions (kg/year):** For systems including diesel backup

G. Software and Simulation Tool

HOMER Pro (Hybrid Optimization of Multiple Energy Resources) was used for:

- Component sizing
- Sensitivity analysis (fuel prices, load growth, irradiance)
- Optimization based on LCOE and reliability
- Visualization of cost breakdowns and system performance

H. Sensitivity Analysis

To ensure robustness of results, a sensitivity analysis was conducted for:

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- Fuel price volatility (₦1000/litre)
- Battery price variation (±20%)
- Solar irradiance fluctuations (±10%)
- Load increase (5–10% growth)

This approach allowed for the identification of the most influential parameters affecting the economic viability of each system configuration.

IV. SYSTEM DESIGN AND CONFIGURATION

This section details the technical setup and component sizing logic for both the **grid-tied** and **standalone** solar energy systems modeled in HOMER Pro. The configurations are designed based on realistic rural load requirements, solar resource availability in West Africa, and component availability in the regional market. Each system is optimized to meet daily household energy demand reliably and economically over a project lifespan of 25 years.

A. Load Demand Assumptions

The system is designed to supply electricity to a small rural community consisting of **five households**, with an aggregated **daily energy demand of 13 kWh/day** and a **peak load of 4 kW**. The load profile includes lighting, mobile phone charging, fans, a television, a refrigerator, and other low-power appliances common in rural homes.

Table 2 Load Demand of Five Households

Appliance	Power Rating (W)	Usage (hrs/day)	Quantity	Daily Energy (Wh)
LED Lighting	10	6	10	600
TV	100	4	2	800
Standing Fan	60	5	3	900
Refrigerator	120	10	1	1200
Phone Charging	5	2	10	100
Miscellaneous	—	—	—	2000

B. Solar Resource Input

- **Location**: West Africa (7–10°N latitude)
- **Average daily solar radiation**: 5.2 kWh/m²/day
- **Monthly variability**: Mild (range: 4.8 – 5.8 kWh/m²/day)

Solar data was imported from **NASA's POWER database** into HOMER Pro for simulation purpose.

C. Grid-Tied Solar PV System Configuration

Component Sizing Logic

- *PV Array:*

$$P_{pv} = \frac{E_{load}}{PSH \times \eta}$$

- *Where:*

- P_{pv} = required PV capacity (kW)
- E_{load} = daily energy demand (Wh/day)
- PSH = average peak sun hours (hours/day)
- η = system efficiency (typically 70% - 80%)

- *Given:*

- E_{load} = 13,000 Wh/day
- PSH = 5.2 hours/day
- η=0.75

$$P_{pv} = \frac{13,000}{5.2 \times 0.75} \approx \frac{13,000}{3.9} \approx 3.33kW$$

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Thus, the required PV array is approximately **3.33 kW**. Rounded up to **3.5 kW** to allow for design margin and performance degradation.

➢ *Inverter:*
The inverter is sized to match or slightly exceed the PV array. A **4.0 kW inverter** is selected for this system to handle the maximum power output comfortably.

➢ *Grid Availability:*
Grid is considered intermittently available, with **daily outages of 6–8 hours** modeled in HOMER to reflect typical conditions in Sub-Saharan rural settings.

➢ *Battery Storage:*
No battery storage is included in this configuration since the grid is expected to provide backup during PV downtime.

Table 3 Component Cost Estimates

Component	Size	Capital Cost	Replacement	O&M (Annual)
PV Panel	3.5 kW	$2,800	$2,400	$35
Inverter	4.0 kW	$500	$400	$20
Grid	—	—	—	Grid tariff = $0.08/kWh

D. Standalone Solar PV System Configuration
Component Sizing Logic

➢ ***PV Array*** (oversized to account for autonomy):

$$P_{pv} = \frac{E_{load}}{PSH \times \eta}$$

➢ *Where:*

- E_{load} = 13,000 Wh/day
- PSH = 5.2 hours/day
- η = 0.70 (assumed slightly lower due to battery losses and standalone inefficiencies)

$$P_{pv} = \frac{13,000}{5.2 \times 0.70} \approx \frac{13,000}{3.64} \approx 3.57kW$$

Rounded up to 4.0 kW to ensure reliability and account for weather variability and panel degradation.

➢ *Battery Bank:*
Required storage:

To size the battery storage for **2 days of autonomy**, factoring in **depth of discharge (DoD)** and **battery efficiency**, we use:

$$E_{storage} = \frac{E_{load} \times \text{days of autonomy}}{\text{DoD} \times \text{efficiency}}$$

Where:

- E_{load}= 13kWh/day
- Days of autonomy = 2
- DoD = 0.8 (80%)
- Efficiency = 0.9 (90%)

$$E_{storage} = \frac{13 \times 2}{0.8 \times 0.9} \approx \frac{26}{0.72} \approx 36.1kWh$$

- **Battery Type**: Lithium-ion (12V, 200Ah)
- **Capacity per unit**:

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$$12V\times200Ah=2{,}400Wh=2.4kWh$$

- *Total units needed:*

$$\frac{36.1kWh}{2.4kWh/unit}\approx15units$$

Thus, a battery bank of **15 lithium-ion units** is required to meet the storage needs.

- *Inverter:*
  Sized to match the PV array → **4.0 kW inverter**

- *MPPT Charge Controller:*
  Must be rated to handle the **maximum PV power of 4.0 kW**, with appropriate voltage and current ratings.

Table 3 Component Cost Estimates

Component	Size	Capital Cost	Replacement	O&M (Annual)
PV Panel	4.0 kW	$3,200	$2,800	$40
Battery	36 kWh	$4,500	$4,000 (after 10 yrs)	$50
Inverter	4.0 kW	$500	$400	$20
Charge Controller	—	$200	$150	$10

- *Optional Diesel Generator:* 2.5 kW ($300/kW) used in sensitivity scenarios for backup.

E. System Simulation Setup in HOMER Pro

- *General Parameters*

- Project duration: **25 years**
- Discount rate: **7%**
- Simulation interval: **Hourly (8760 points/year)**
- Currency: **USD**

- *Scenario Definitions*

- **Scenario A**: Grid-tied PV + unstable grid
- **Scenario B**: Standalone PV + battery (no grid)
- **Scenario C** *(optional)*: Standalone hybrid (PV + battery + diesel backup)

Each configuration was optimized in HOMER Pro using the search space approach, allowing the software to evaluate multiple sizing combinations and determine the least-cost, most reliable solution.

Table 4 Summary of System Designs

Parameter	Grid-Tied System	Standalone System
PV Capacity	3.5 kW	4.0 kW
Battery	None	36 kWh
Inverter	4.0 kW	4.0 kW
Grid Access	Yes (unstable)	No
Generator	Optional	Optional
Backup Reliability	Depends on grid	Battery & solar only
Initial Cost	Lower	Higher
Maintenance	Lower	Moderate

V. RESULTS AND DISCUSSION

A. Monthly Energy Demand vs. PV Generation (Fig. 1)

The monthly energy consumption and associated photovoltaic (PV) energy generation for a hypothetical rural community in Sub-Saharan Africa are illustrated in Figure 1. With peak usage taking place between June and August due to an increase in home and agricultural activities, the monthly energy demand ranges from 390 kWh to 450 kWh.

PV generation consistently exceeds demand throughout the year, reaching its highest levels during the dry season months of March to May, thanks to increased solar irradiance. This outcome indicates that a properly sized PV system can reliably meet the energy needs of rural areas and even produce surplus energy. The surplus offers opportunities for future load increase, microgrid extension, or efficient energy use. The graphic illustrates the technical viability of solar photovoltaic systems under these climatic conditions, confirming their appropriateness for rural electrification in Sub-Saharan countries, where energy demands are generally moderate and solar resources are abundant.

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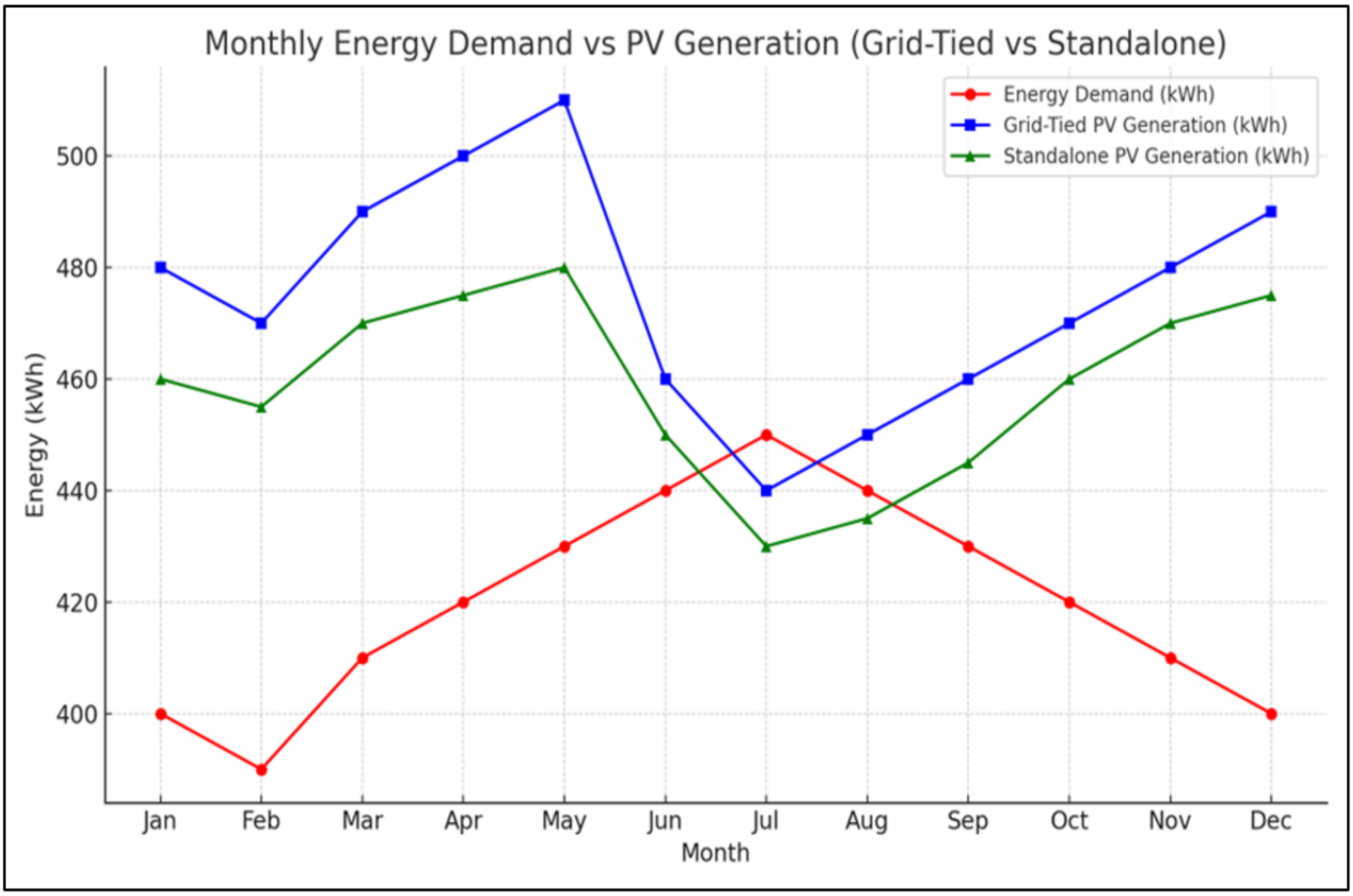

Fig 1 Monthly Energy Demand vs PV Generation

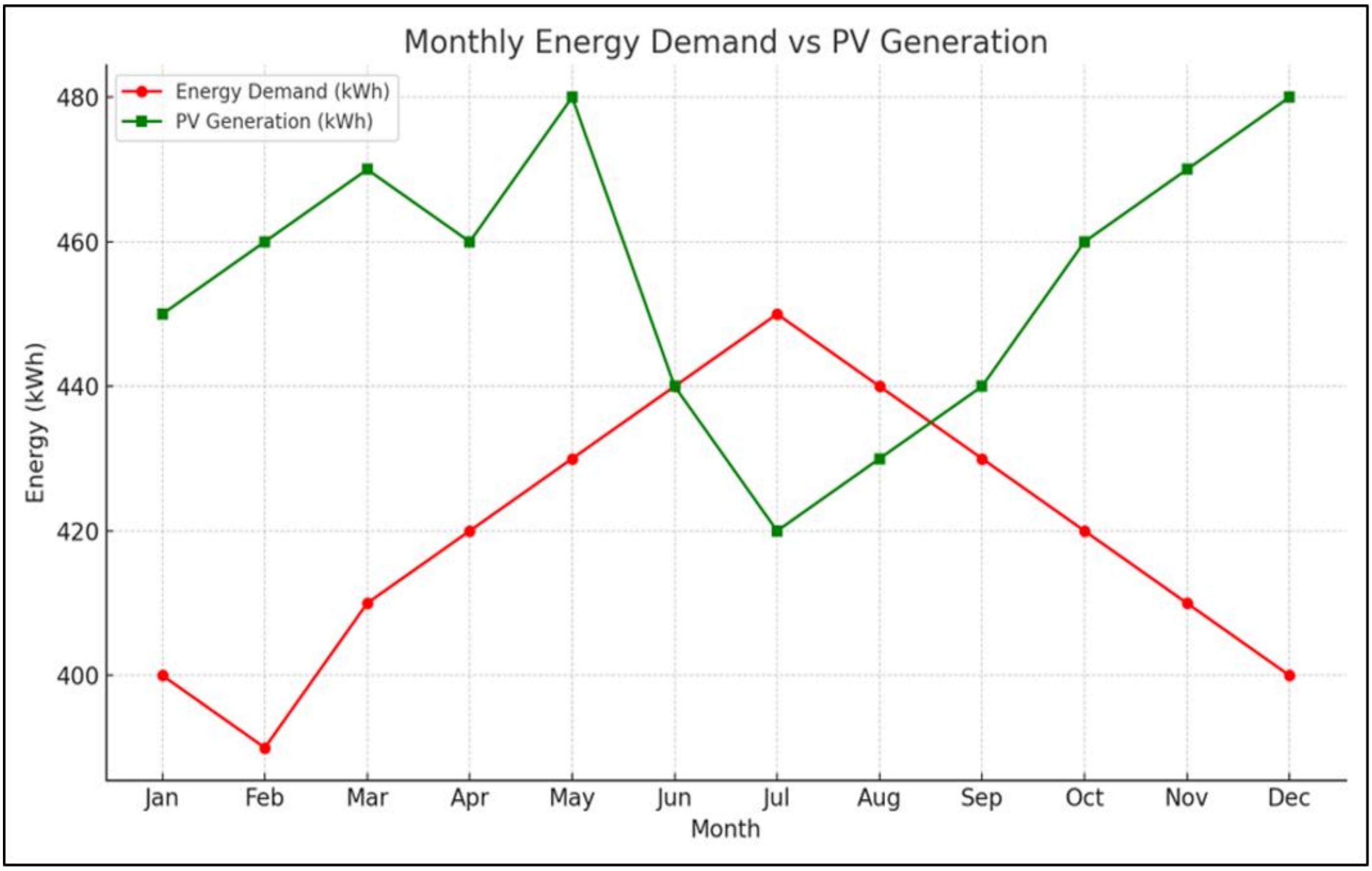

Fig 2 Comparison of Grid-Tied and Standalone PV Systems

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B. Comparison of Grid-Tied and Standalone PV Systems (Fig. 2)

Fig. 2 compares energy demand against PV generation for both grid-tied and standalone system configurations. The grid-tied PV system outperforms the standalone system in energy yield across all months. This is primarily due to the elimination of battery-related losses and the potential for surplus power to be exported to the grid.

Photovoltaic (PV) generation and energy consumption are contrasted in Figure 2 for both grid-tied and freestanding system types. In every month, the grid-tied PV system continuously produces more electricity than the standalone system. The capacity to export excess power back to the grid and the removal of battery-related losses are the primary causes of this benefit.

In contrast, the standalone system, while capable of meeting the community's demand in most months, shows marginal underperformance in July and August. These periods typically coincide with increased cloud cover, underscoring the need for carefully sized battery storage and backup generation in off-grid scenarios.

From an engineering-economic standpoint, the grid-tied system offers higher efficiency and cost-effectiveness when grid availability is moderate to stable. However, the standalone system remains essential for fully off-grid or remote regions, where grid extension is economically prohibitive.

Generally speaking, the standalone system can satisfy community demand in the majority of months, however it tends to perform marginally worse in July and August. This deficiency typically occurs when cloud cover increases, emphasising the significance of appropriately scaled battery storage and off-grid backup generation. The grid-tied system is more efficient and cost-effective from a technical and economic standpoint when the grid is moderately to extremely stable. But in places that are completely off the grid or in remote locations where expanding the grid is not practical, the standalone system is essential.

VI. CONCLUSION

This study conducted a comparative engineering and economic analysis of grid-tied and standalone solar PV systems using HOMER software, with a focus on rural electrification in Sub-Saharan Africa. The results indicate that both configurations are technically viable and capable of meeting the energy demands of a typical rural community.

Grid-tied systems demonstrated higher energy yields and system efficiency due to their ability to export excess power and avoid storage losses. On the other hand, standalone systems, while slightly less efficient, offer energy independence and are crucial in locations without grid access.

Overall, solar PV, grid-tied or standalone presents a reliable and sustainable energy solution for rural electrification. The proper configuration depends on site-specific conditions such as grid reliability, energy demand profiles, and financial constraints.

Using HOMER software, this study compared the engineering and economic aspects of standalone and grid-tied solar photovoltaic (PV) systems, with a focus on rural electrification in Sub-Saharan Africa. According to the findings, both arrangements are technically feasible and capable of supplying the energy needs of an average rural population. Because grid-tied systems may export excess power and prevent storage losses, they have shown higher energy yields and improved efficiency. On the other hand, even if they are marginally less effective, independent systems offer energy independence and are crucial in places without grid connectivity. All things considered, solar PV—whether grid-connected or independent—represents an accurate and environmentally friendly energy option for electrifying rural areas.

The optimal configuration depends on site-specific conditions such as the reliability of the grid, energy demand profiles, and financial constraints.

POLICY IMPLICATIONS

The findings of this study have several important policy implications for rural energy planning and investment in Sub-Saharan Africa:

- Supportive regulatory frameworks such as net-metering, feed-in tariffs, and mini-grid licensing are essential to enhance the adoption of grid-tied systems.
- Targeted subsidies and concessional financing should be made available for standalone PV systems, especially in off-grid areas where commercial viability is limited.
- Integrated rural electrification strategies should prioritize solar-based solutions due to their scalability, low environmental impact, and alignment with Sustainable Development Goal 7.
- Governments and development partners should invest in local capacity building, technical training, and community ownership models to ensure the long-term sustainability of solar energy projects.

By aligning technical design with financial and policy instruments, solar PV systems, both grid-tied and standalone can play a transformative role in achieving universal electrification across rural Sub-Saharan Africa.

The findings of this study highlight several important policy implications for rural energy planning and investment in Sub-Saharan Africa:

- *Supportive Regulatory Frameworks:*

Implementing supportive regulations such as net metering, feed-in tariffs, and mini-grid licensing is essential to promote the adoption of grid-tied systems.

- *Targeted Financial Support:*

Targeted subsidies and concessional financing should be made available for standalone photovoltaic (PV) systems,

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particularly in off-grid areas where commercial viability is often limited.

- *Integrated Rural Electrification Strategies:*

Rural electrification strategies should prioritize solar-based solutions due to their scalability, low environmental impact, and alignment with Sustainable Development Goal 7.

- *Capacity Building and Community Ownership:*

Governments and development partners should invest in local capacity building, technical training, and community ownership models to ensure the long-term sustainability of solar energy projects. By aligning technical design with financial and policy instruments, both grid-tied and standalone solar PV systems can play a transformative role in achieving universal electrification across rural Sub-Saharan Africa.

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