Techno-Feasibility Assessment of Solar Photovoltaic Integration for Household Electricity Supply and Mini Electric Vehicle Charging in Northwestern Nigeria

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Abstract
The integration of solar photovoltaic (PV) technology with residential electricity consumption and electric vehicle (EV) charging offers a promising pathway towards sustainable energy utilisation and low-carbon transportation, particularly in regions experiencing unreliable electricity supply. This study investigates the technical potential of solar PV generation for meeting household electricity demand and supporting mini electric vehicle charging in Aliero, Kebbi State, northwestern Nigeria. The investigation employs hourly meteorological datasets obtained from the Photovoltaic Geographical Information System (PVGIS) for the period 2016–2025. Solar PV electricity generation was estimated using a standard performance-based modelling approach, while module operating temperature and household electricity demand were evaluated to establish the temporal compatibility between renewable energy generation and consumption. The proposed system incorporates a 3 kWp solar PV configuration, battery energy storage, household electrical loads, and a 13.2 kW mini electric vehicle charging system. The simulated PV system achieves a maximum power output of approximately substantially exceeding the maximum household demand which is indicating the availability of surplus daytime solar electricity that could be strategically allocated to battery storage and subsequent EV charging. However, the available PV generation is insufficient to independently satisfy the rated 13.2 kW EV charging requirement, highlighting the importance of appropriately sized battery storage, supplementary grid support, and intelligent energy management. The findings demonstrate the technical potential of solar PV integration for improving residential electricity availability and supporting sustainable electric mobility in Aliero and it provides a useful framework for decentralised renewable energy planning and the development of integrated household–electric vehicle energy systems in solar-rich, electricity-deficient communities.

Keywords: *Solar photovoltaic system; Electric vehicle charging; Household electricity demand; Solar irradiance; Renewable energy integration; Aliero*

1 Introduction

Sustainable electricity and transportation, has become the grand challenges of twenty-first century from political, economic and societal point of view. Utilization of fossil fuels for transportation and energy related issues is among the biggest culprit of anthropogenic carbon emission, accounting for about 60% of the global CO_2 emission. Electricity as the backbone of development of any society, has already contributed 37.5% of the total CO_2 emission in the

globe releasing 7700 million tonnes of CO_2 annually, this is an indication that, serious transition is necessary in decarbonising electricity across the globe (Phattanaviroj et al., 2025; Gado et al., 2020; Shata, 2012). To address this challenging issue, several potential solutions to sustainable electricity generation for large, medium and small scale electricity generation are highlighted in the literature with renewable energy technologies having wider acceptance as the sustainable solution among all the suggested solution (Gwani and Abubakar, 2016; Guorui et al., 2017). However, the unique features of replenishing made renewable energy sources suitable candidates for energy application despite being prone to several limitations unlike the conventional energy sources. Renewable energy sources such as solar energy, wind energy, small hydro, geothermal energy etc. are clean energy sources that offer the promise of meeting energy demand for both on-grid and off-grid applications, as well as, application to electric vehicles despite the intermittency effect (Obada et al., 2024). The simplest solution methodology that could be adopted to solve the effect of intermittency of renewable energy sources in electricity generation in the real time and simulation environments, is to look at the generation at diurnal level i.e. hourly level of generation (Gwani et al., 2020; Abubakar et al., 2019). Solar energy is attractive as substitute for the conventional electricity generation and sustainable transportation due to its abundant nature, clean and safe nature in terms of energy conversion processes (Maghami, 2025). Studies confirmed that, Nigeria receives solar radiation of about 5.08×10^{12} kWh of energy per day because it is in the region of lower latitude of the earth (Onyeka, 2026). With the amount of solar energy reaching Nigeria, if solar conversion technologies are used to capture this energy from the sun with only 5% efficiency which is the lowest efficiency of solar technology designs to covered only 1% of the Nigerian surface area, 2540GWh of electricity can be generated. This shows that with government fiscal incentives and enabling policies, Nigeria can become the leading renewable solar electricity and sustainable transportation leading country in the globe. This study conducts an extensive investigation to identify the viability of solar PV system for electricity generation and application to mini electric vehicle, at a Aliero, Kebbi State, Northwestern Nigeria. The system is proposed to deliver smoother power to a typical household based on electricity demand of a typical household and electricity demand of the selected mini electric vehicle.

2.0 Materials and Methods

2.1 The Study Area

Aliero, a municipal town and the administrative center of the Aliero local government in Kebbi State, is positioned in the southeastern region of Kebbi State (Fig.1). Aliero lies within the coordinates of 12°16′42″N latitude and 4°27′6″E longitude. Similar to other regions in northwestern Nigeria, Aliero is rich in renewable energy resources, particularly solar energy. However, despite the abundant solar energy, Aliero grapples with a severe electricity shortage, which is essential for the advancement of any society worldwide. Many areas within Aliero experiences extremely low voltage and inconsistent power supply throughout the day.

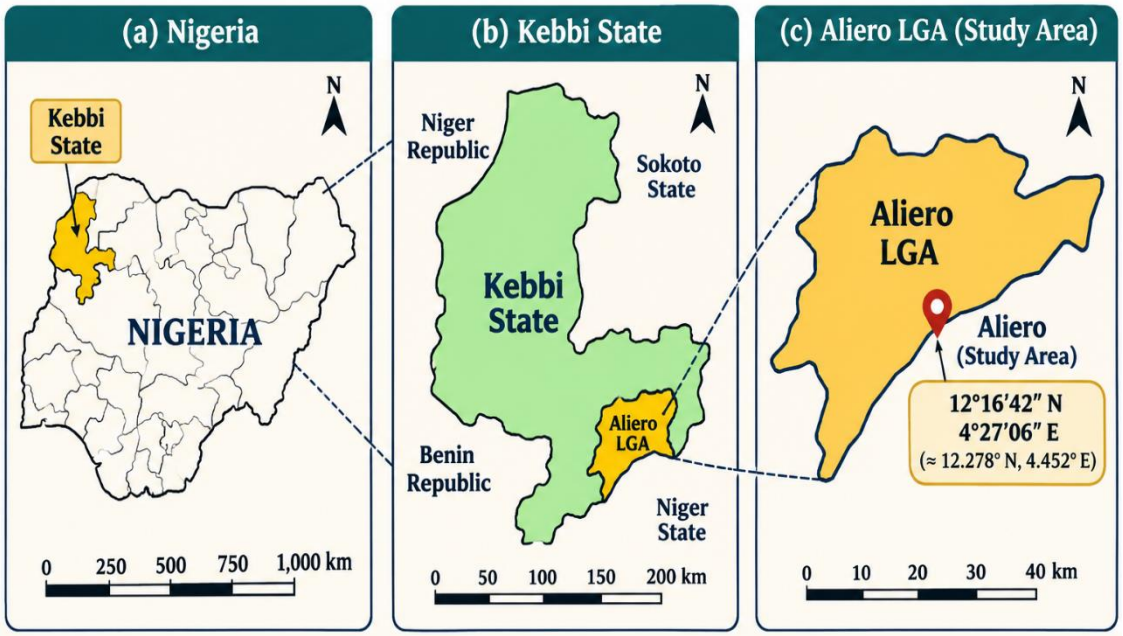

Fig 1. Geographic localization of Aliero (Gado et al., 2025)

2.2 Solar Irradiation Data

Solar radiation dataset is the key parameter for the determination of solar PV output at all time and location. Several solar radiation data sources exist across the globe but none of them is perfect. The most common types of solar radiation data source include ground measurements and satellite-based measurement or calculations. Several problems are attached to ground solar radiation measurements. The most common being failure of the measuring device itself, covering of the sensor by dirt, frost, snow, shadow by the buildings and tree across the year.

The research utilized PVGIS 2016-2025 meteorological datasets recorded at 10m above the ground with resolution of 2x2 km is adopted in this study. Starting with the PVGIS metadata, solar, wind, temperature and other required datasets are extracted using machine learning, intelligent automation, data analytics, and predictive modelling. More specifically, in order to improve the accuracy of the data utilised in this study, the extracted hourly datasets is subjected to thorough analysis for conversion to one-year datasets having at least 100% of valid data. The converted one-year datasets were grouped into seasons of the year: Winter (December, January, February), summer (March, April, May), monsoon (June, July, August, September) and post monsoon (October, November) using machine learning and intelligent automation.

2.3 Insolation and Solar Power Output Modelling

Using the extracted irradiation data and the solar panel parameters given in Table 1, the solar PV power output is calculated using the global benchmark model for estimating solar PV electricity generation (Equ. 1).

$$E = A\, r\, G_i\, PR \qquad (1)$$

Where,

E =Energy Output (W), A =Total solar panel Area (m^2), r = solar panel yield (%) G_i = Global Horizontal Irradiance. PR = Performance ratio (0.75)

The *Performance Ratio (PR)* is very essential value for evaluating the quality of PV installation independent of the orientation or inclination of the panel i.e. it is taking account of all system loses.

However, the module operating temperature T_{mod} is calculated in this study by employing Equ. 2 using ambient temperature T_{amb} and Global Horizontal Irradiance G_i. This model is proposed in this study in calculating the module operating temperature for comparison with the selected PV module Nominal Operating Cell Temperature (NOCT).

$$T_{mod} = T_{amb} + 0.035G_i \quad (2)$$

Where, T_{mod} = Module operating temperature T_{amb} = Ambient temperature G_i = Global Horizontal Irradiance.

2.4 Electricity Demand Assessment

Hourly electricity consumption of a typical household in countries like Nigeria is very difficult because of the erratic nature of electricity supply across the all the regions.

Several enabling methodologies have been adopted in generating a typical household electricity demand profile. Methodologies recently explored in the literature include interpolation method (Gado et al. 2015), ANN (Artificial Neural Networks) (Guorui et al., 2017, Gajowniczek and Zabkowski, 2017), genetic algorithm (Ozturk et al., 2015), multiple regression method (Widén et al. 2012), have been successfully utilised in this regard. However, most of these methodologies are utilised in locations where there is constant and uninterrupted power supply which has created a concern for utilizing the approaches in locations with intermittent power supply. This study utilized PVGIS typical household electricity demand profile. PVGIS electricity demand profile Fig. 2. The electricity demand profile is based on the consumption of all the electrical appliances connected to load of a typical household, during 24-hours of the day. The PVGIS electricity demand profile is based on several considerations that are valid based on real time studies that takes account of even the effects of unexpected weather conditions (Gado et al., 2025).

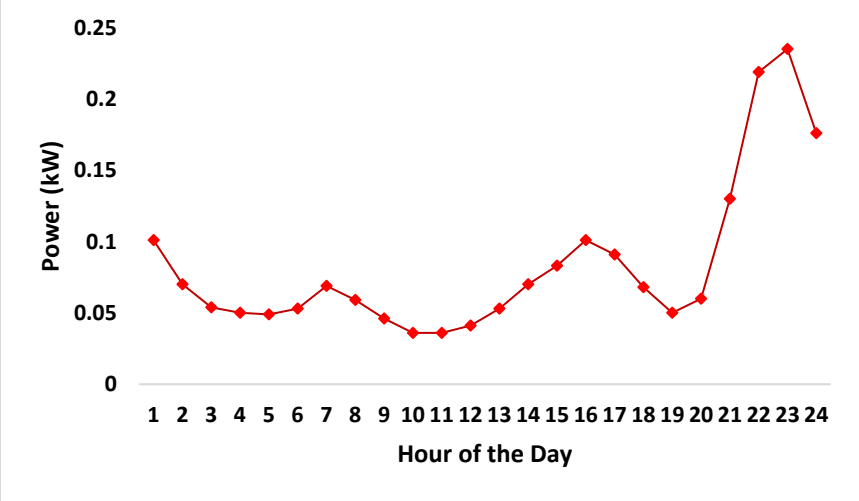

Fig. 2: Typical household electricity demand profile

2.2.4 The System Components

To achieve the objectives of this research, three major components are considered in modelling and analysis of the designed system which includes solar PV system, battery storage system and the selected mini electric vehicle as depicted in Fig 3.

The solar PV system and the battery storage system and the Electric Vehicle Supply Equipment (EVSE) are connected to a DC bus. While the typical household electricity load is connected to AC bus through DC-AC converter. The system is proposed to supply the full electricity demand of typical household, and the excess power from the solar PV system will be

channelled to the battery storage system until it is fully charged. The battery storage system will help in meeting the electricity demand of the proposed system in the absence of power output from the RESs. The specifications and parameters of the selected solar PV system at Standard Test Condition (STC) and the technical specifications of the Electric Vehicle are given in Table 1 and 2 respectively.

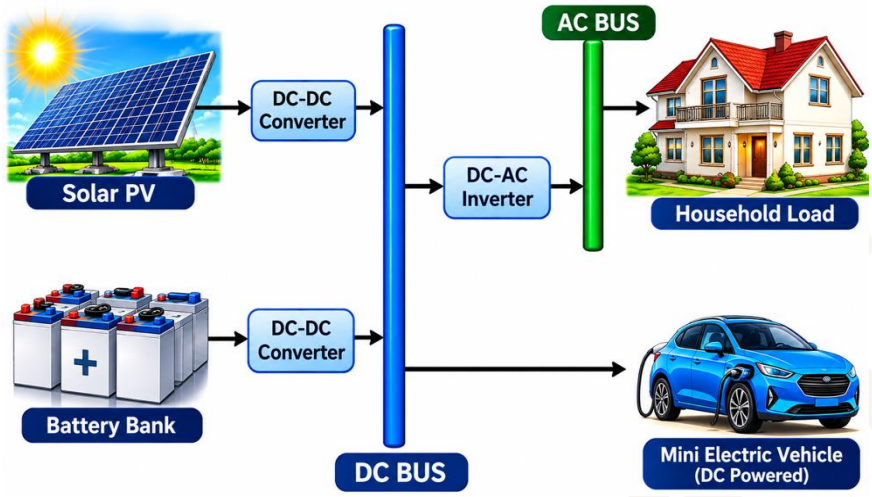

Fig. 3 Proposed system optimisation

Table 1: Technical parameters of iPower Monocrystalline Solar Panel at Standard Test Conditions (STC)

Parameter	Value
Nominal power (W)	320
Panel area (m^2)	1.6
Operating Voltage (V)	12
Short-circuit current I_{SC} (A)	9.54
Voltage at maximum power V_{MPP} (V)	35.84
Maximum power current I_{MPP} (A)	8.92
Module efficiency (ŋ%)	20.54
Operating temperature range (°C)	-40 and +85

(Source: Zinox, 2026)

Table 2: Specifications of the Electric Vehicle (EV) utilised in the study (Sources: PONY , 2026).

Parameter	Value
Power	13.2kW
Power supply	Lithium Iron phosphate battery (BMS)
Battery	48V/280Ah
Top speed	100 kmh^{-1}
Mileage	170 km
Full charge time	4~7 hours
Motor	Permanent Magnet Synchronous Motor (PMSM)
Load Capacity	600kg
Outline Size (mm):	3160 x 1490 x 1580

3.0 Results and Discussions

Figure 4a, presents the monthly variation in solar irradiance for the year 2025. The results indicate a noticeable seasonal variation in solar radiation availability, with estimated irradiance values ranging from approximately 121 W/m² to 230 W/m². The highest value was recorded in January (230 W/m²), followed by December (225 W/m²), while the lowest value occurred in August (121 W/m²). This observation indicates that solar irradiance availability was relatively higher during the beginning and end of the year compared with the middle months. The relatively high irradiance observed in January and December indicates favourable periods for solar electricity generation, whereas the lower values recorded between June and August highlight the importance of incorporating adequate energy storage and effective energy management strategies.

Fig. 3b shows the monthly mean solar irradiation and power output across months of the year and estimated power output from the solar PV system utilised in the study. The results signified the direct correlation between power output and the irradiation falling on the surface of the solar PV system. The results clearly indicate the accuracy of the generic model utilized in estimating the power output utilized in the studies.

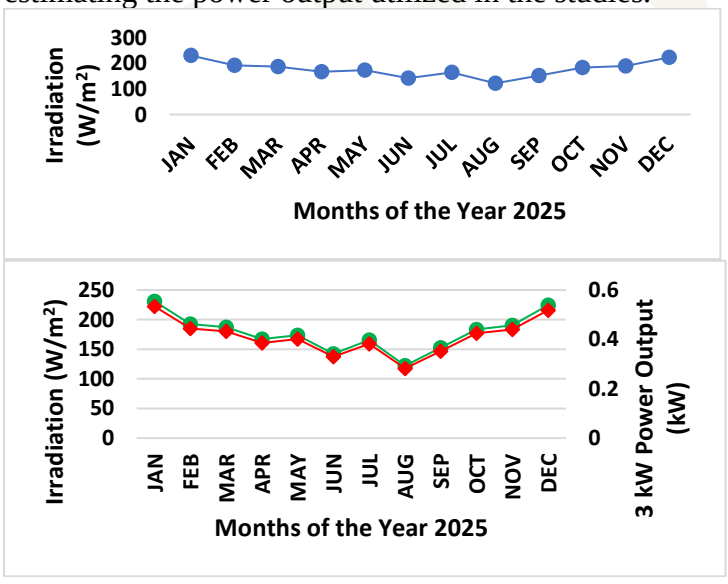

Fig. 4. (a) Monthly mean solar irradiation (b) Monthly mean solar irradiation and power output across months of the year

The results in Fig. 5, illustrates the monthly variation in ambient temperature throughout the year 2025. The temperature profile shows a clear seasonal pattern, characterized by a gradual

increase from January to May, followed by a general decline towards August, a moderate recovery between September and November, and another decrease in December. The observed variations are relevant to the performance assessment of solar photovoltaic (PV) systems because ambient temperature influences PV module operating temperature, conversion efficiency, and overall electricity generation

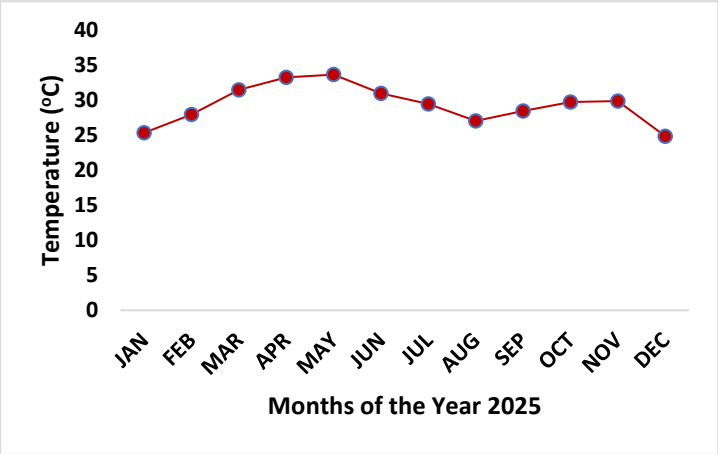

Fig. 5. Monthly mean ambient temperature

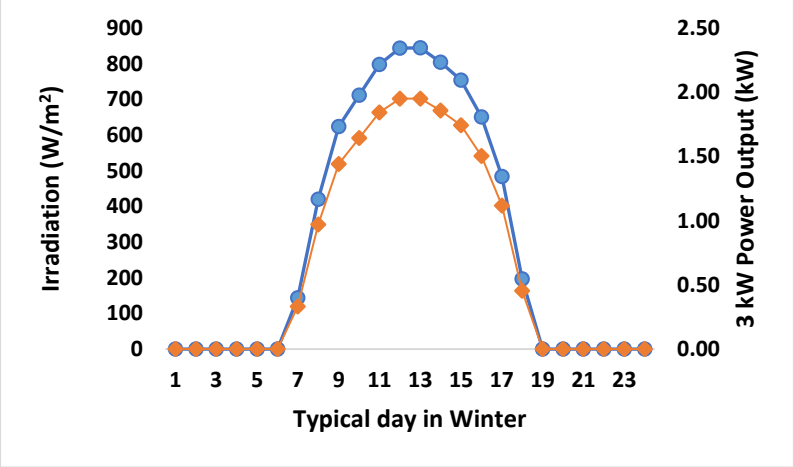

Fig. 6: Diurnal variation of solar irradiation and corresponding power output of a 3 kWp photovoltaic system during a typical winter day in 2025.

Fig. 6 illustrates the diurnal variation of solar irradiation and the corresponding power output of a 3 kWp photovoltaic (PV) system during a typical winter day in 2025 at Aliero. The results show the close correspondence between the irradiation and power output profiles throughout the day. Nevertheless, the PV power output does not increase in exact proportion to solar irradiation because photovoltaic conversion efficiency is also influenced by operating temperature, module characteristics, inverter efficiency, and other environmental factors. In addition, the difference between the morning and afternoon profiles may be associated with variations in module temperature and atmospheric conditions.

Overall, the results indicate that the 3 kWp PV system demonstrates a predictable diurnal generation pattern during the winter season, with its highest energy production occurring around solar noon. The relatively high peak irradiation suggests favourable solar resource availability even during winter. However, the limited duration of peak generation and the reduction in output during early morning and late afternoon hours highlight the importance of

considering seasonal solar availability when estimating daily energy yield, sizing battery storage, and designing PV systems for reliable electricity supply.

Fig. 7, illustrates the comparison between the hourly solar photovoltaic (PV) power output and typical household electricity demand during a winter day in Aliero. The results reveal a significant variation in solar power generation throughout the day, while household electricity demand remains relatively low and fluctuates moderately over the 24-hour period.

Overall, the results demonstrate the potential of solar photovoltaic technology to satisfy household electricity demand during a typical winter day. However, the temporal mismatch between peak solar generation and peak household consumption emphasises the need for an appropriately sized battery storage system to ensure a more reliable and continuous electricity supply.

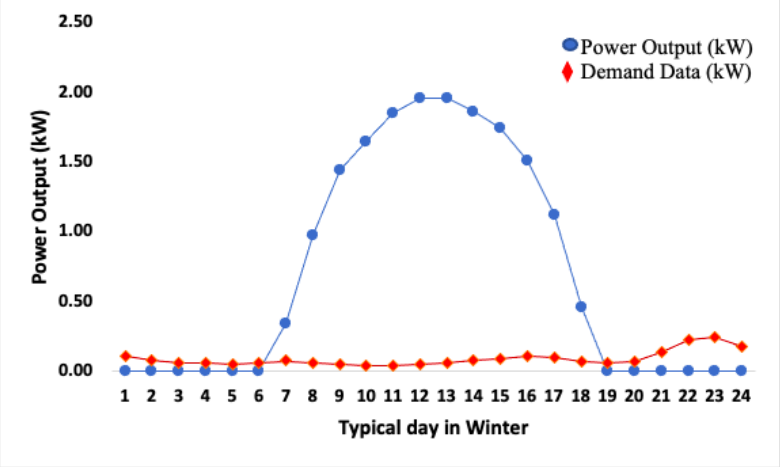

Fig. 7: Solar Power Output comparison with typical House hold Demand Data in Aliero

5. Conclusion

This study has investigated the potential of solar photovoltaic (PV) technology for integrated household electricity supply and mini electric vehicle (EV) charging in Aliero, Kebbi State, northwestern Nigeria, using meteorological datasets, PV performance modelling, and household electricity demand assessment. The findings establish the technical relevance of solar PV integration as a decentralised energy solution for communities characterised by abundant solar resources but unreliable conventional electricity supply.

The results demonstrate a pronounced seasonal variation in solar energy availability, with monthly mean solar irradiance ranging from approximately 121 W/m² in August to 230 W/m² in January. This variation confirms that the performance of solar PV installations in the study area is strongly influenced by seasonal meteorological conditions and underscores the need to incorporate seasonal resource variability into system sizing and operational planning. The diurnal assessment further indicates that the proposed 3 kWp PV system achieves a maximum simulated power output of approximately 1.95 kW between 12:00 and 13:00, whereas the typical household electricity demand reaches only about 0.24 kW. The considerable difference between generation and residential consumption identifies an opportunity for productive utilisation of surplus renewable electricity rather than allowing the available generation capacity to remain underutilised. A particularly important finding concerns the integration of the proposed PV system with the 13.2 kW mini electric vehicle charging system. Although the available solar generation can contribute to EV charging, its maximum output remains substantially below the vehicle's rated charging power requirement which indicates that the direct solar charging alone cannot guarantee charging at the rated capacity. This finding establishes the importance of appropriately designed battery energy storage, supplementary

grid electricity where available, and intelligent energy management strategies for coordinating household consumption, PV generation, battery state of charge, and EV charging requirements. Such coordination could improve renewable energy utilisation, reduce dependence on conventional electricity supply, and enhance the operational flexibility of the proposed integrated energy system. The principal contribution of this research lies in its location-specific assessment of the relationship between solar PV generation, residential electricity demand, and mini EV charging in an electricity-deficient environment in northwestern Nigeria. The findings are particularly relevant to renewable energy developers, policymakers, and stakeholders interested in expanding sustainable transportation infrastructure in regions with significant solar energy potential. Overall, the study concludes that solar PV integration offers a technically promising approach to connecting residential electricity supply with emerging electric mobility applications in Aliero. However, achieving reliable and sustainable operation requires an appropriately sized hybrid energy architecture rather than reliance on PV generation alone. The proposed integration framework therefore represents a useful foundation for advancing decentralised renewable electricity systems and low-carbon transportation in Nigeria and other solar-rich developing regions.

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