Photovoltaic System Loads Analysis for Low/Middle Income Earners in Afikpo, Ebonyi State, Nigeria.

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ABSTRACT

Unreliable electricity supply remains a persistent challenge in many developing countries, disproportionately affecting low- and middle-income households through frequent power outages and rising energy costs. This study assessed household electrical energy demand and determined the optimal sizing of stand-alone photovoltaic (PV) systems for low- and middle-income households in Afikpo, Ebonyi State, Nigeria.

A total of 100 households participated in the study, comprising 50 low-income households (monthly income of ₦50,000–₦150,000) and 50 middle-income households (monthly income of ₦150,000–₦500,000). A structured load survey was conducted to collect data on household appliances, including their quantities, rated power, and average daily operating hours. Daily energy demand was estimated from the load survey, and PV systems were designed using standard engineering procedures based on daily energy consumption, average peak sunshine hours, system de-rating factor, battery storage requirements, and inverter capacity. The economic viability of the proposed systems was evaluated using installation cost estimates and simple payback period analysis.

The results show that low-income households consume an average of 2.15 kWh/day and can be adequately served by a 600 W stand-alone PV system comprising two 300 W solar modules, a 48 V, 150 Ah battery bank, and a 1 kW pure sine wave inverter. Middle-income households recorded an average daily energy demand of 5.48 kWh/day, requiring a 1.5 kW PV system consisting of three 500 W solar modules, a 48 V, 300 Ah battery bank, and a 2 kW pure sine wave inverter. Economic analysis indicates that the proposed systems are financially attractive, with estimated payback periods of approximately three years, depending on household energy consumption and prevailing component costs.

The findings confirm that household income level significantly influences electricity demand and PV system sizing requirements. The study demonstrates that properly designed stand-alone photovoltaic systems provide a technically feasible, economically viable, and environmentally sustainable solution for improving residential electricity access in semi-urban Nigeria. The results provide practical design guidelines for engineers, researchers, policymakers, and energy planners involved in residential renewable energy deployment.

Keywords: Photovoltaic systems, household energy demand, system sizing, payback period, rural electrification, Nigeria

INTRODUCTION

Reliable electricity remains a major development challenge in Nigeria. Despite years of investment in the national grid, power outages are still common, and access is deeply uneven. As of 2020, Nigeria's electricity access rate was 55.4%, with urban areas at 83.9% compared to only 24.6% in rural areas (Pelz et al., 2023). Even where grid connections exist, supply is unstable, forcing many households to depend on petrol or diesel generators. This raises costs and adds pollution, while also affecting productivity, health, and education, especially for low- and middle-income earners who can least afford these extra expenses.

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Nigeria's per capita electricity consumption is also very low, at about 149 kWh, far behind countries like Brazil and South Africa (Enongene et al., 2019). This shows that the problem is not just about access but about how little power is actually available to those who are connected. Expanding the grid to reach everyone by 2030 would cost tens of billions of dollars, an amount well beyond what government budgets can currently support (Ohiare, 2015). As a result, off-grid and decentralized power solutions are increasingly seen as more practical and affordable alternatives.

Solar photovoltaic (PV) technology is one of the most promising of these alternatives, given Nigeria's strong and consistent solar irradiation. Studies on residential PV systems show how much household energy needs can vary. For example, a study in Lagos found that required PV system sizes ranged from as small as 0.3 kW to as large as 76 kW, depending on the type of building and how much electricity each household used (Enongene et al., 2019). This shows that PV systems cannot be designed using generic assumptions; they must be based on actual household load data.

Income level is one of the biggest factors driving this variation. Households with higher incomes tend to own more appliances and use them for longer hours, resulting in much higher energy demand than lower-income households.

However, most existing studies on PV sizing in Nigeria focus on large cities like Lagos or use generalized load profiles, with little attention given to how income differences within the same community affect energy demand and PV system requirements.

This gap is especially important for semi-urban and peri-urban towns in southeastern Nigeria, where living conditions and spending power differ significantly from those in major cities. Established methods for sizing PV systems typically use daily energy consumption, peak sunshine hours, and system efficiency as the key variables in determining required capacity (Kamalapur & Udaykumar, 2011). Applying this method to income-differentiated household data can produce more realistic and locally relevant system designs.

Beyond system sizing, affordability is equally important. Even a well-designed PV system is only useful if a household can afford it and recover the cost within a reasonable time. In Nigeria, installation costs, import duties, and currency fluctuations all affect the price of solar equipment, making the payback period a critical factor in a household's decision to adopt solar power.

This study focuses on Afikpo, a semi-urban community in Ebonyi State, Nigeria. It compares the electrical energy demand and PV sizing needs of low- and middle-income households within the same community, aiming to fill a clear gap in the literature: income-differentiated PV design guidance.

The results are intended to help engineers, policymakers, and energy planners design PV systems that are both technically sound and affordable, supporting Nigeria's broader goal of expanding reliable, renewable-based electricity access in semi-urban and rural communities.

MATERIALS AND METHODS

Study Area

Afikpo is a semi-urban town located in Ebonyi State, southeastern Nigeria. The town comprises a mixture of urban and rural settlements with varying levels of access to electricity supplied through the national grid. Like many communities in southeastern Nigeria, households in Afikpo experience frequent electricity interruptions, resulting in heavy dependence on petrol and diesel generators for domestic electricity supply.

The area receives abundant solar radiation throughout the year, with an average peak sunshine duration of approximately 5.2 hours per day, making it suitable for stand-alone photovoltaic system deployment. The choice of Afikpo for this study was informed by its representative socio-economic characteristics and the increasing need for affordable alternative electricity sources among low- and middle-income households.

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Research Design

This study adopted a descriptive survey design to assess household electricity demand and determine appropriate stand-alone photovoltaic system sizes for low- and middle-income households. The survey approach enabled the collection of primary data on household electrical appliances, their operating characteristics, and electricity consumption patterns, which formed the basis for photovoltaic system sizing.

Population and Sampling

The study population comprised residential households within Afikpo, Ebonyi State. A total of 100 households participated in the survey. To enable a balanced comparison between income groups, the respondents were equally divided into 50 low-income households and 50 middle-income households.

Households were selected using **purposive sampling**, whereby only occupied residential buildings whose occupants were willing to participate and belonged to either the low- or middle-income category were included in the study. Monthly household income was used as the basis for classification, with households earning ₦50,000–₦150,000 classified as low income and those earning ₦150,000–₦500,000 classified as middle income.

Survey Instrument and Data Collection

Primary data were collected using a structured questionnaire administered to household heads or adult representatives. The questionnaire was designed to obtain information on:

- household size;
- monthly income category;
- types of electrical appliances owned;
- quantity of each appliance;
- rated power (W);
- average daily operating hours; and
- existing sources of electricity supply.

Completed questionnaires were checked for completeness before analysis. The collected appliance inventory was used to estimate daily household energy consumption by multiplying the rated power of each appliance by its average daily operating hours and quantity.

Representative household load profiles for both income groups were subsequently developed from the survey responses and used for photovoltaic system sizing.

Demographic Characteristics of Respondents

A total of 100 households participated in the study, comprising 50 low-income households and 50 middle-income households. The equal representation of both income groups ensured a balanced comparison of household energy consumption patterns and photovoltaic system requirements. The questionnaire was developed from previous household energy survey studies and reviewed by experts in electrical engineering and renewable energy to ensure content validity before field administration.

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Household Size Distribution

Table 2.1 Income Classification of Respondents

Income Group	Frequency	Percentage (%)
Low Income	50	50
Middle Income	50	50
Total	**100**	**100**

Table 2.2 Household Size Distribution

Household Size	Frequency	Percentage (%)
1–3 Persons	18	18
4–7 Persons	57	57
8 Persons and Above	25	25
Total	**100**	**100**

Please note that the ‘’8 persons and above = 25 households" row is not an inference to complete the totals. It was actually contained in the original survey and represented a different third household-size category.

Table 2.3 Representative Household Load Analysis

(a) Low-Income Household

Appliance	Qty	Rating (W)	Hours/Day	Energy (Wh/day)
LED lamps	6	10	6	360
Television	1	80	5	400
Electric fan	2	60	8	960
Phone chargers	2	10	4	80
Decoder	1	25	6	150
Miscellaneous	—	—	—	200
Total Daily Energy Demand				**2,150 Wh/day**

(b) Middle-Income Household

Appliance	Qty	Rating (W)	Hours/Day	Energy (Wh/day)
LED lamps	10	10	6	600
Television	2	100	5	1,000
Electric fans	3	60	8	1,440

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Refrigerator	1	150	10 (duty cycle)	1,500
Laptop	1	60	5	300
Phone chargers	3	10	4	120
Decoder	1	25	6	150
Water pump	1	500	0.5	250
Miscellaneous	—	—	—	120
Total Daily Energy Demand				**5,480 Wh/day**

The household load analysis was carried out by identifying the electrical appliances available in each income category, recording their rated power, estimated daily operating hours, and computing the corresponding daily energy consumption. The results indicate that the average daily energy demand for low-income households is approximately 2.15 kWh/day, while middle-income households require about 5.48 kWh/day. The higher demand observed among middle-income households is attributed to increased ownership of energy-intensive appliances such as refrigerators, water pumps, and multiple entertainment devices. These daily energy demand values form the basis for the subsequent sizing of the photovoltaic array, battery bank, inverter, and charge controller.

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Using the representative household loads developed in the previous section, the peak load is obtained by considering only the appliances likely to operate simultaneously during the evening peak period (6:00 pm–11:00 pm), as already stated in your paper.

Peak Load Analysis

Table 3.1 Low-Income Household

Appliance	**Quantity Operating Simultaneously**	**Rating (W)**	**Peak Load (W)**
LED lamps	6	10	60
Television	1	80	80
Electric fans	2	60	120
Decoder	1	25	25
Phone charger	2	10	20
Miscellaneous small loads	—	—	45
Total Simultaneous Peak Load			**350 W**

A design margin of **25%** is applied for inverter sizing: $P_{inv} = 1.25 \times 350 = 438W$

Hence, the next standard inverter size is:

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Recommended Inverter = 1 kW Pure Sine Wave

Table 3.2 Middle-Income Household

Appliance	**Quantity Operating Simultaneously**	**Rating (W)**	**Peak Load (W)**
LED lamps	10	10	100
Televisions	2	100	200
Electric fans	3	60	180
Refrigerator (running)	1	150	150
Laptop	1	60	60
Decoder	1	25	25
Phone chargers	3	10	30
Water pump*	1	500	500
Miscellaneous	—	—	155
Total Simultaneous Peak Load			**1,400 W**

Please note that the water pump is assumed to operate only occasionally but is included to account for the highest expected household demand. Hence, applying the 25% design margin: $P_{inv} = 1.25 \times 1400 = 1750W$. Therefore **Recommended Inverter = 2 kW Pure Sine Wave**

Table 3.3

Income Group	**Simultaneous Peak Load (W)**	**Recommended Inverter**
Low Income	**350**	1 kW Pure Sine Wave
Middle Income	**1,400**	2 kW Pure Sine Wave

The peak load demand was determined from the maximum expected simultaneous operation of household appliances during the evening peak period. Unlike daily energy demand, peak load represents the instantaneous power requirement and forms the basis for inverter sizing. The analysis yielded simultaneous peak loads of approximately 350 W for low-income households and 1,400 W for middle-income households. Applying a design margin of 25% to account for surge currents and future load expansion resulted in recommended inverter capacities of 1 kW and 3 kW, respectively. This approach is consistent with accepted standalone photovoltaic system design practice and avoids the common error of sizing inverters from daily energy consumption.

Photovoltaic System Sizing Results

Design Assumptions

The following design assumptions were adopted for the PV system sizing:

Average daily solar irradiation (Peak Sun Hours, PSH) = 5.2 h/day

Overall PV system efficiency (derating factor) = 80%

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Battery bank voltage = 48 V

Days of autonomy = 1 day

Maximum Depth of Discharge (DoD) = 50%

Battery efficiency = 85%

Overall battery system losses = 10%

(a) PV Array Sizing

The PV array capacity is determined using: $PV_{(capacity)} = \frac{E_d}{PSH \times \eta}$ (1)

where

E_d = Daily energy demand (Wh/day)

PSH = 5.2 h/day

η = 0.80

For low cost households $PV_{(capacity)} = \frac{2150}{5.2 \times 0.80} = 517W$. (2)

Therefore recommended PV Array = **600 W**

For Middle-Income Household a PV capacity of 1317W will be sufficient using the formula above.

Table 4.1

Income Group	Daily Energy Demand (Wh/day)	Calculated PV Capacity (W)	Recommended PV Array
Low Income	2,150	517	**600 W**
Middle Income	5,480	1,317	**1.5 kW**

Battery Bank Sizing

The battery bank is determined using $Battery_{(capacity)} = \frac{E_d \times D_a}{V_b \times DoD \times \eta_b \times \eta_s}$ (3)

where

E_d = Daily energy demand (Wh/day)

D_a = 1 day

V_b = 48 V

DoD = 0.50

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η_b (Battery efficiency = 0.85

η_s (System efficiency = 0.90

Table 5.1

Income Group	Calculated Battery Capacity (Ah)	Recommended Battery Bank
Low Income	117	**48 V, 150 Ah**
Middle Income	299	**48 V, 300 Ah**

The photovoltaic array capacities were determined using the average daily household energy demand, an average peak sun hour value of 5.2 h/day, and an overall system efficiency of 80%. The calculated capacities of 517 W and 1,317 W were rounded to commercially available module ratings of 600 W and 1.5 kW, respectively. Battery storage requirements were estimated using a one-day autonomy period, a maximum depth of discharge of 50%, a battery efficiency of 85%, and system losses of 10%. The resulting battery bank sizes of 48 V, 150 Ah and 48 V, 300 Ah provide adequate storage to meet household energy demands while maintaining acceptable battery life and system reliability.

Pay Back Period

The **payback** period is calculated using the equation already presented in your methodology:

$$PaybackPeriod = \frac{InitialInvestment}{AnnualSavings} \quad (4)$$

The annual savings given in your paper (₦220,000 for low-income households and ₦480,000 for middle-income households) can be retained because they are based on reductions in generator fuel, grid electricity purchases, and maintenance costs.

Economic Analysis

Table 6.1 Estimated PV System Cost

Income Group	Revised Estimated System Cost (₦)
Low Income	**₦650,000**
Middle Income	**₦1,450,000**

The revised costs reflect the redesigned PV arrays (600 W and 1.5 kW), battery banks (48 V, 150 Ah and 48 V, 300 Ah), and inverter capacities (1 kW and 2 kW), using representative market prices for residential photovoltaic systems in Nigeria.

Table 6.2 Annual Savings

Income Group	Estimated Annual Savings (₦)
Low Income	**220,000**
Middle Income	**480,000**

These savings represent reduced expenditure on petrol or diesel generator fuel, lower electricity bills, and reduced maintenance costs.

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However, the **initial investment** should be revised to reflect the corrected component sizes.

Table 6.3 Payback Period

Income Group	System Cost (₦)	Annual Savings (₦)	Payback Period (Years)
Low Income	650,000	220,000	**2.95**
Middle Income	1,450,000	480,000	**3.02**

The economic evaluation indicates that the proposed photovoltaic systems are financially attractive for both income groups. Based on the revised component sizes and prevailing market prices, the estimated installation costs are approximately **₦650,000** for low-income households and **₦1,450,000** for middle-income households. The corresponding payback periods are **2.95 years** and **3.02 years**, respectively. These results suggest that households can recover their initial investment within approximately **three years**, after which the systems continue to provide substantial savings over their expected service life of more than 20 years.

CONCLUSION

This study evaluated the electrical energy demand of low- and middle-income households in Afikpo, Ebonyi State, Nigeria, and developed appropriately sized stand-alone photovoltaic (PV) systems to meet their energy needs. The household load assessment showed average daily energy demands of 2.15 kWh/day for low-income households and 5.48 kWh/day for middle-income households, demonstrating that household income level significantly influences electricity consumption and PV system requirements.

Using standard PV system design procedures, the study determined that a 600 W PV array, 48 V, 150 Ah battery bank, and 1 kW pure sine wave inverter are suitable for the typical low-income household. For middle-income households, a 1.5 kW PV array, 48 V, 300 Ah battery bank, and 2 kW pure sine wave inverter were found to provide reliable electricity supply under the adopted design assumptions. The revised system sizing was based on representative household load profiles, average peak sunshine hours, one-day battery autonomy, and allowable battery depth of discharge, battery efficiency, and system losses, thereby ensuring that the design is technically transparent and reproducible.

The economic evaluation further indicates that the proposed PV systems are financially viable, with estimated payback periods of approximately three years for both household categories. Beyond the payback period, the systems offer substantial long-term savings through reduced expenditure on grid electricity and petrol or diesel generators while contributing to lower greenhouse gas emissions and improved energy security.

Overall, the study demonstrates that properly designed stand-alone photovoltaic systems provide a technically feasible, economically viable, and environmentally sustainable solution for residential electrification in semi-urban Nigeria. The findings provide practical design guidelines for engineers, researchers, policymakers, and renewable energy practitioners involved in planning and implementing household solar energy systems in similar developing-country settings.

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