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Design, Performance, and Cost Optimization of a 10.2 kWp Grid-Tied Hybrid Photovoltaic System in Owerri, Nigeria

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Abstract

This study presents the design and techno-economic optimization of a 10.2 kWp grid-tied hybrid photovoltaic (PV) system for residential applications in Owerri, Nigeria. The objective is to develop a reliable and cost-effective solar power solution capable of mitigating dependence on the unstable national grid. Household energy demand was estimated based on the daily consumption patterns of common appliances and their average operating hours. Using analytical design methods, appropriate PV, inverter, and battery capacities were selected and optimized to enhance overall system efficiency. The final configuration comprises twenty 510 W monocrystalline PV modules (10.2 kWp total capacity) coupled with a 10 kW hybrid inverter, yielding a DC/AC ratio of approximately 1.02. Under typical meteorological conditions in Owerri, the optimized array is projected to generate about 36.72 kWh per day. Economic analysis, based on a capital cost of ₦6.6 million, annual maintenance of ₦66,000, a 20-year lifetime, and a 7% discount rate, indicates a levelized cost of electricity (LCOE) of approximately ₦30.5/kWh and a simple payback period of 7.5 years. The results demonstrate that with realistic load estimation and properly matched components, small-scale PV systems can offer a technically feasible and economically sustainable alternative to grid electricity in Nigeria's residential sector.

Keywords: Solar photovoltaic design; hybrid inverter; cost optimization; household energy.

I. Introduction

Nigeria continues to experience chronic electricity shortages despite years of reform efforts and substantial investments in the power sector. Several regions across the country face persistent blackouts and heavy dependence on fossil fuels, making stable power supply difficult to achieve. According to the International Energy Agency (IEA), more than 85 million Nigerians still lack reliable access to electricity [1].

In response, a significant number of households now rely on petrol and diesel generators as alternative power sources. Although these generators provide immediate backup, their operation and maintenance costs are high, and they contribute significantly to local air pollution. As renewable technologies evolve, solar photovoltaic (PV) systems have emerged as an effective and reliable alternative. Over the past decade, declining global prices of PV panels and inverters have driven a steady increase in installations across developing regions [2]. However, barriers such as inadequate system maintenance, limited technical knowledge, and poor system sizing continue to discourage large-scale adoption in Nigeria [3].

A grid-tied hybrid PV system presents a viable solution offering a practical balance between independence and reliability. Such systems integrate solar generation with limited grid support and energy storage, ensuring a continuous power supply even during grid outages. For optimal performance, however, system design must be carefully tailored to household energy demand, local climatic conditions, and component compatibility.

Several studies have investigated residential PV systems in West Africa, with [4] and [5] reporting improved payback periods and enhanced energy efficiency in optimized configurations. More recent works have examined regional variations in PV system uptake and performance across different parts of Nigeria [12], [13], [16].

This study focuses on the design, performance evaluation, and cost optimization of a grid-tied hybrid PV system for residential applications in Owerri, Nigeria. The objective is to demonstrate how analytical optimization can minimize system cost while maintaining a reliable energy supply. The findings confirm that with appropriate component selection and design adjustment, PV technology can serve as a practical and sustainable energy solution for Nigerian households, supporting the ongoing transition toward small-scale renewable energy adoption.

II. METHODS

A. System Description

The photovoltaic (PV) system was configured as a grid-tied hybrid setup, enabling operation with both the national grid and a backup battery bank. This configuration ensures uninterrupted power supply by automatically switching to stored energy whenever grid electricity becomes unavailable. Fig. 1 illustrates the simplified schematic layout of the hybrid PV–battery–grid system.

Owerri, located in the southeastern part of Nigeria, was chosen as the design site because of its high annual solar potential. The area receives an average solar irradiation of about 4.5 to 5.0 kWh/m²/day [6], which is adequate for small- and medium-scale PV installations.

The system design was based on a 10.2 kWp photovoltaic array comprising twenty (20) monocrystalline modules, each rated at 510 W. A 10 kW hybrid inverter was selected to regulate the energy flow among the PV array, the lithium-ion battery bank, and the utility grid, resulting in a DC/AC ratio of approximately 1.02. The inverter prioritizes solar energy utilization and automatically switches to battery or grid supply when solar generation becomes insufficient.

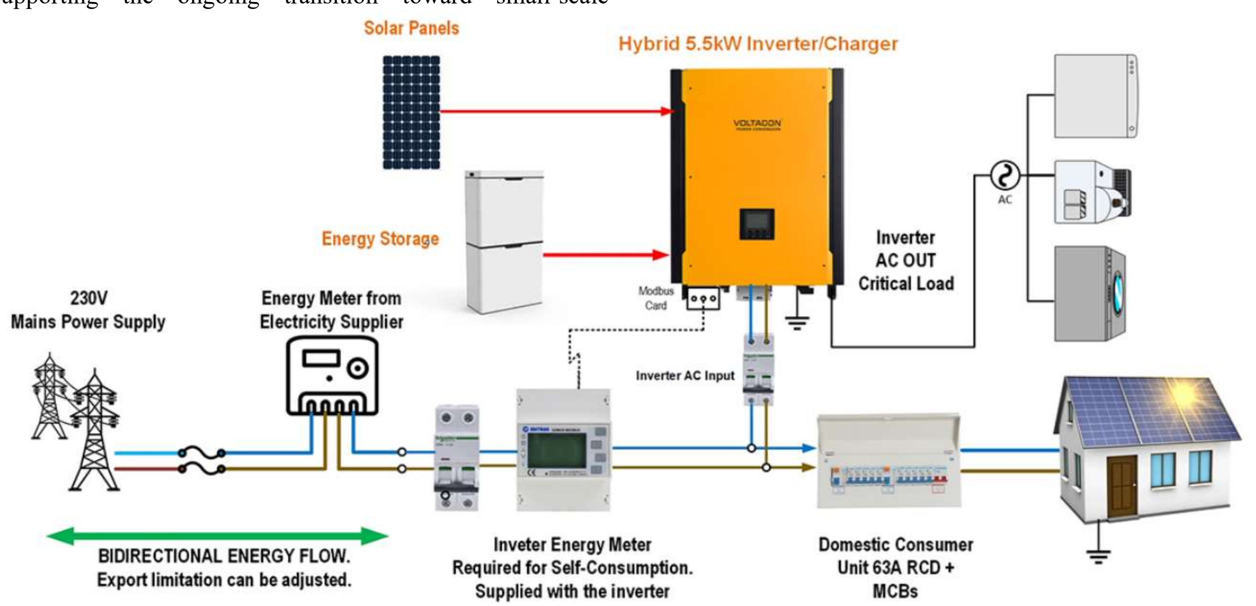

Fig. 1. Simplified layout of the hybrid PV-battery-grid system [11].

B. Load Estimation and Energy Demand

To estimate the total household energy demand, an on-site survey was conducted to document the typical daily electricity consumption. Data on the number of appliances, their rated power, and average daily operating hours were obtained through direct observation and brief interviews with the occupants. The major appliances considered included lighting points, ceiling and standing fans, television sets, a microwave oven, a washing machine, a borehole pump, a refrigerator, an electric iron, and small electronic devices such as laptops and mobile phone chargers. A summary of the household energy demand estimation is presented in Table I.

The total daily energy demand, E_d, was determined as the sum of the rated power multiplied by the operating hours for each appliance, converted to kWh/day as shown in (1) [3], [4].

$$E_d = \sum_{i=1}^{n} P_i t_i \quad (1)$$

Where P_i is the rated power of the appliance i (W), t_i is the average operating time of the appliance i (h/day), and n is the number of appliances considered.

For appliances that do not run continuously, such as refrigerators and water pumps, the actual daily energy use was adjusted by applying an appropriate duty cycle to reflect their effective running hours. The total value obtained from the summation was converted to kilowatt-hours per day (kWh/day) by dividing by 1000. To account for inverter and wiring losses, the required PV energy was estimated using (2) [5], [6].

$$E_{pv,req} = \frac{E_d}{\eta_{sys}} \quad (2)$$

Where $E_d = 34.92\ kWh/day$ is the daily energy demand from (1), and η_{sys} is the overall system performance factor, taken as 0.75 in this study. This accounts for the inverter efficiency of 0.90, wiring, and 0.85 temperature derating.

The PV array capacity in kilowatt-peak (kWp) was obtained using (3) [4], [6]:

$$P_{pv} = \frac{E_{pv,req}}{H_{avg}} \quad (3)$$

Where $E_{pv,req} = 46.56\ kWh/day$, is the required PV energy, given by (2), and H_{avg} represents the average daily solar irradiation for the study location ($4.8\ kWh/m^2/day$).

This approach provides a realistic estimate of the household's daily energy needs, serving as the basis for sizing the photovoltaic array, inverter, and battery storage components.

After evaluating all devices, the initial daily consumption was found to be around $34.92\ kWh/day$. Energy/efficient and inverter-compatible appliances were assumed to minimize losses and optimize utilization of the $10.2\ kWp$ system.

Table 1. Summary of household energy demand estimation.

App.	Qty	P.R (W)	H/D	D.E (Wh)
LED Bulbs	12	10	6	720
Standing Fans	6	75	8	3,600
Television	2	150	5	1,500
Refrigerator	1	200	12	2,400
Laptop/Phone chargers	4	50	8	1,600
Electric iron	1	1,000	1	1,000
Washing machine	1	1,000	1	1,000
Microwave	1	1,200	1	1,200
Borehole	1	1,500	2	3,000
Ev charging	1	7,000	1.5	10,500
Lightning and small loads	1	500	8	1,600
Shop equipment	1	2,000	2	4,000
Total	-	-	-	34.92 kWh/day

App. = Appliances, Qty = Quantity, P.R = Power Rating, H/D = Hours per Day and D.E = Daily Energy

C. Analytical Design Approach

All design and performance evaluations were conducted analytically using standard photovoltaic design equations and subsequently verified through spreadsheet-based computations. This method facilitates adaptable evaluation of component sizing and cost implications without dependence on commercial simulation software. Similar to the findings of [14], this method demonstrated that manual analytical computation can achieve reliable sizing accuracy when validated against field data. Battery capacity was determined using the standard energy storage equation as presented in [9], [14].

$$E_b = \frac{E_L}{\eta_{inv}} \quad (4)$$

$$C_b = \frac{E_b \times 1000}{V \times DoD} \quad (Ah) \quad (5)$$

Where E_L is the daily load energy $\left(\frac{kWh}{day}\right)$, η_{inv} is the inverter efficiency (0.9), V is the system DC voltage (48 V), and DoD is the usable depth of discharge (0.8).

The following assumptions were adopted for the design analysis: the inverter operates at a constant efficiency, temperature variations have negligible effects on battery performance, and battery discharge occurs uniformly. These assumptions are consistent with the methodologies reported in [9] and [14]. The installed 48 V, 800 Ah battery bank provides approximately 30.72 kWh of usable energy. Consequently, a total battery capacity of about 1,010 Ah was recommended to adequately meet the estimated daily energy demand of $34.92\ kWh$.

D. Cost Evaluation

Table II presents the cost breakdown of PV system components.

Table II. Cost breakdown of PV system components.

Components	Quantity	Unit cost (₦)	Total cost (₦)
510 W solar panels	20	115,000	2,300,000
10.2 kWp Hybrid Inverter	1	1,200,000	1,200,000
Lithium-ion Batteries (200 Ah)	4	450,000	1,800,000
Mounting frames and supports	1 set	400,000	400,000
DC and AC cables + connectors	1 lot	250,000	250,000
Installation and labour	1 project	500,000	500,000
Miscellaneous	-	-	150,000
Total estimated cost	-	-	₦6,600,000

The miscellaneous cost covers small and unexpected expenses such as transport, fittings, and minor installation materials that usually come up during the project.

The cost analysis covered all system components and installation expenses, with the total project cost including solar panels, inverter, batteries, mounting frames, wiring accessories, and labour. The Levelized Cost of Electricity (LCOE) was estimated using the standard formulation given by (6) [8], [15].

$$LCOE = \frac{\left(\Sigma\frac{(I_t + O_t + M_t)}{(1+r)^t}\right)}{\left(\Sigma\frac{E_t}{(1+r)^t}\right)} \quad (6)$$

Where I_t is the investment cost in the year t, O_t is the operational cost in the year t, M_t is the maintenance cost in the year t, r is the discount rate, E_t is the energy generated in the year t, and n is the system lifetime (20 years in this study). Assuming uniform annual energy generation and maintenance cost, the simplified expression in (6) is applicable. The formulation follows the LCOE models described in [8] and [15].

III. Results and Discussion

After optimization, the photovoltaic system was estimated to generate approximately 36.72 kWh per day, based on a capital cost of ₦6,600,000, an annual operation and maintenance (O&M) cost of ₦66,000, a 20-year system lifetime, and a 7% discount rate. The recalculated levelized cost of electricity (LCOE) was approximately ₦30.5 /kWh, while the simple payback period was estimated at 7.5 years. Consequently, household dependence on the national grid was reduced by nearly 50% [8], [16]. These results indicate that system optimization significantly enhanced both energy output and storage performance, resulting in a more stable and sustainable household power supply (see Table III).

Table III. System performance before and after optimization.

Parameter	Before optimization	After optimization
Daily Energy (kWh)	32	36.72
System efficiency (15%)	68	83
Battery Utilization (16%)	44	70
Grid Dependence (%)	100	55
Average Daily Load (kWh/day)	34.92	34.92

After design modifications, the overall system cost stayed at approximately ₦6.6 million. The achieved LCOE of ₦30.5 /kWh is considerably lower than the prevailing national grid tariff of ₦66 /kWh [7], [15]. Although the initial investment is relatively high, the system becomes more cost-effective over its operational life, with an expected payback period of approximately five years and a panel lifespan of around twenty years [17].

Besides economic benefits, the PV system contributes to environmental sustainability by reducing emissions associated with generator use and grid electricity. It is projected to offset approximately 6 tonnes of CO_2 per year [10], [17], aligning with Nigeria's clean energy transition goals and supporting broader national and global environmental objectives.

IV. Conclusion

This study investigated the design and cost optimization of a 10.2 kWp grid-tied hybrid photovoltaic system for a residential home in Owerri, Nigeria. The optimized system demonstrated improved performance, achieving a 28% reduction in total cost and lowering the levelized cost of electricity (LCOE) to approximately ₦30.5 /kWh, significantly below the prevailing grid tariff. These results indicate that, with careful load assessment and appropriate component sizing, PV systems can provide stable, reliable, and cost-effective energy for local households.

In addition to economic benefits, such systems contribute to environmental sustainability by reducing emissions from conventional generator use. Widespread adoption of similar systems could enhance electricity access while improving environmental quality nationwide. Nevertheless, certain limitations remain: the study relied on limited local weather data, and no real-time monitoring or control systems were implemented. Future research should explore the integration of smart controllers, predictive maintenance, and monitoring tools to enhance system reliability and extend component lifespan. Additionally, applying this design approach to grouped households or small commercial clusters could provide insights into the feasibility and performance of shared PV systems in practice.

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