

Design And Sizing of A Standalone Solar PV System for Rural Primary Health Centers in Nigeria: A Techno-Economic Assessment

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Abstract- *The attainment of universal health coverage and the Sustainable Development Goals (SDGs), particularly SDG 3 (Good Health and Well-being) and SDG 7 (Affordable and Clean Energy), is fundamentally contingent upon the availability of reliable electricity. In Nigeria, the energy deficit in the healthcare sector is acute, with approximately 40% of functional Primary Health Centers (PHCs) completely devoid of grid access, and the remainder suffering from chronic intermittency that compromises critical services such as vaccine cold chains, emergency obstetric care, and diagnostic testing. This research presents a comprehensive, expert-level design and techno-economic analysis of a standalone Solar Photovoltaic (PV) system tailored for a rural PHC in Nigeria. By synthesizing meteorological data across Nigeria's geopolitical zones contrasting the high-insolation North (Sokoto/Kaduna) with the cloud-prone South (Port Harcourt) the study establishes a robust "worst-case" sizing methodology. The design integrates a 4.4 kWp monocrystalline PV array, a 20 kWh Lithium Iron Phosphate (LiFePO₄) battery energy storage system (BESS), and a 5 kVA hybrid inverter, engineered to support a daily load of approximately 7.0 kWh. The economic analysis, grounded in 2025 market data, reveals a Levelized Cost of Electricity (LCOE) of approximately \$0.14/kWh for the solar solution, compared to over \$0.60/kWh for diesel generation. The findings demonstrate that while the initial capital expenditure for solar is higher, the Life Cycle Cost (LCC) is significantly lower, offering a payback period of under two years against a diesel baseline.*

Africa. In Nigeria, estimates suggest that only 20% of the roughly 30,000 PHCs are functional, and among those, roughly 40% have no access to electricity whatsoever. Even facilities nominally connected to the grid face chronic unreliability, with power availability often averaging a mere 6 to 10 hours per day.

The consequences of this energy starvation are severe. Unreliable power disrupts the cold chain required for vaccine storage, leading to spoilage and reduced immunization coverage. It forces health workers to conduct night-time deliveries using kerosene lanterns and batter torchlight, increasing the risk of maternal mortality, and renders diagnostic equipment like microscopes and centrifuges unusable.

1.2 The Justification for Standalone Solar PV

Standalone Solar Photovoltaic (PV) systems emerge as the definitive solution for rural healthcare electrification in Nigeria due to the country's abundant solar resources. Average daily solar radiation ranges from approximately 3.5 kWh/m²/day in the coastal southern zones to 7.0 kWh/m²/day in the semi-arid northern regions. Furthermore, the transition from Lead-Acid to Lithium Iron Phosphate (LiFePO₄) batteries has revolutionized off-grid reliability, offering cycle lives exceeding 10 years and greater resilience to high ambient temperatures.

I. INTRODUCTION

1.1 Background: The Energy-Health Nexus in Nigeria
The "energy-health nexus" represents one of the most critical developmental challenges facing sub-Saharan

II. METHODOLOGY

2.1 Design Philosophy and System Architecture
The design philosophy is one of deterministic reliability, employing a "worst-case scenario" method.

The system architecture follows a standard DC-coupled configuration appropriate for standalone applications, as illustrated in Figure 1.

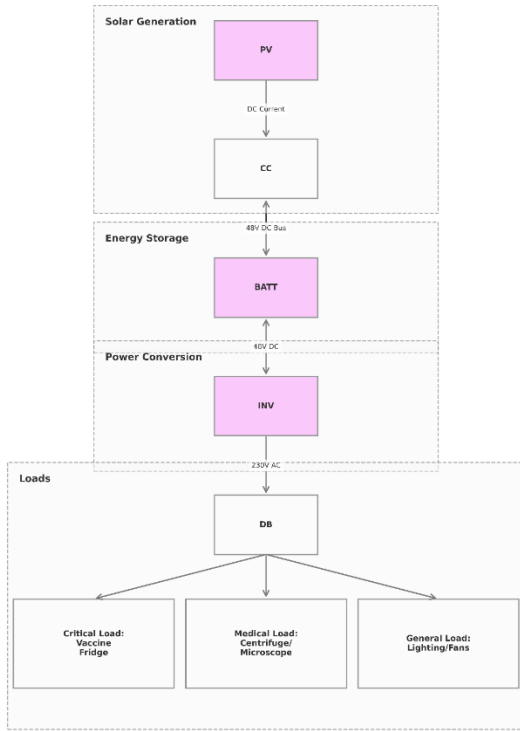


Figure 1: Block diagram of the proposed Standalone Solar PV System Architecture for a Rural PHC.

The flowchart accurately visualizes the system components and connections defined in the code:

- Solar Generation: Contains the PV panels and Charge Controller (CC), connected by DC Current.

- Energy Storage: Contains the Battery (BATT), connected via a 48V DC Bus.
- Power Conversion: Contains the Inverter (INV), converting 48V DC to 230V AC.
- Loads: Shows the Distribution Board (DB) feeding critical, medical, and general loads.

The components PV, BATT, and INV are highlighted in pink as specified

2.2 Site Selection and Data Sources

Solar irradiation data was analyzed for two distinct locations to ensure national applicability:

1. Kaduna (North West): High insolation, representing the dry Sahelian climate.
2. Port Harcourt (South South): Low insolation, representing the humid, cloud-prone coastal climate.

Data was sourced from the NASA Prediction of Worldwide Energy Resources (POWER) Project and validated against Nigerian Building and Road Research Institute (NBRI) data.

III. LOAD ASSESSMENT AND PROFILE

3.1 Load Analysis

A detailed inventory of appliances was compiled based on WHO Performance, Quality and Safety (PQS) standards for cold chain equipment and typical rural clinic requirements. The load profile is categorized into Critical (must run 24/7) and Non-Critical loads.

Table 1: Estimated Daily Load Profile for a Rural PHC

Appliance Category	Appliance Name	Qty	Power (W)	Hrs/Day	Daily Energy (Wh)	Priority
Medical	Vaccine Fridge (PQS)	1	80	24	800	Critical
	Clinical Centrifuge	1	100	1	100	High
	LED Microscope	1	5	3	15	High
	Tabletop Autoclave	1	1500	0.5	750	Medium

General	LED Tube Lights	10	15	8	1,200	High
	Security Lights	4	20	12	960	High
	Ceiling Fans	4	70	8	2,240	Low
	Laptops/Phones	-	-	-	900	Medium
TOTAL			~2.5 kW		~6,965 Wh	

3.2 Energy Consumption Distribution

To visualize the energy demand, Figure 2 breaks down the consumption. Notably, ventilation (fans) and lighting constitute a significant portion of the load, while the critical vaccine fridge consumes relatively less but requires 100% reliability.

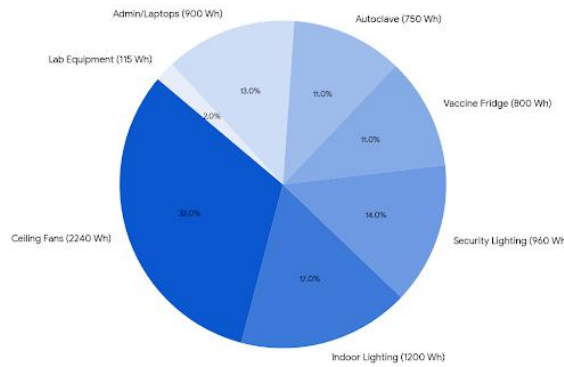


Figure 2: Energy Consumption Distribution

IV. SOLAR RESOURCE ASSESSMENT

The sizing relies on the "worst-case month" to ensure the system does not fail during the rainy season. As shown in Figure 3, there is a significant disparity between the North (Kaduna) and South (Port Harcourt).

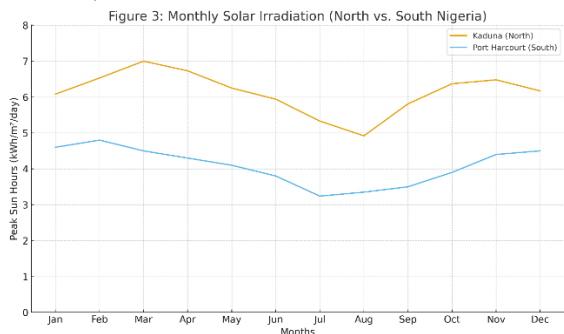


Figure 3: Monthly Solar Irradiation (North vs. South Nigeria)

Figure 3: Monthly Solar Irradiation (North vs. South Nigeria) compares the average Peak Sun Hours (kWh/m²/day) across 12 months for two Nigerian locations:

- Kaduna (North Nigeria)
- Port Harcourt (South Nigeria)

Peak Sun Hours represent the intensity of sunlight available for solar energy generation. Higher values indicate better solar production potential.

Kaduna (North Nigeria) – Higher and More Stable Solar Potential

Kaduna shows consistently higher solar irradiation throughout the year, ranging roughly between 5.0 and 7.0 kWh/m²/day.

Seasonal Pattern

- Peak irradiation occurs in March (7.0) and remains high from February to May.
- A gradual decline appears during the rainy season (June–August), reaching a low of 4.92 in August.
- Irradiation rises again toward the end of the year.

Interpretation

This trend reflects the semi-arid climate of Northern Nigeria, where:

- Dry seasons have clear skies and intense sunlight.
- Rainy seasons slightly reduce sunlight due to cloud cover.

Implication:

Kaduna is highly suitable for solar installations, offering strong year-round generation.

Port Harcourt (South Nigeria) – Lower and More Fluctuating Solar Potential

Port Harcourt records significantly lower Peak Sun Hours, ranging from 3.2 to 4.8 kWh/m²/day.

Seasonal Pattern

- The highest irradiation (approx. 4.8) appears in February.
- A consistent decline follows into mid-year, reaching a minimum of 3.24 in July.
- Slight recovery begins in August–December, but values remain lower compared to Kaduna.

Reason for the Lower Values

This matches the humid, rainy, and cloudy climate of Southern Nigeria:

- High moisture content and frequent rainfall block solar radiation.
- Cloud cover reduces peak sun hours especially from June to September.

Implication:

Solar systems in Port Harcourt require larger PV arrays or hybrid support (battery, grid, generator) to meet the same energy demand.

Table 2: North vs. South: Direct Comparison

Observation	Kaduna (North)	Port Harcourt (South)
Sun hours	Higher (5–7)	Lower (3–5)
Seasonal drop	Moderate	Significant (rainy season impact)
Best months	February – April	January – March
Worst months	August	July

Overall Insight

- Northern Nigeria clearly outperforms Southern Nigeria in solar availability.
- System design in the South must consider oversizing, better storage, or hybridization.

Design Decision: The system is sized using 3.24 kWh/m²/day (Port Harcourt in July) to guarantee functionality anywhere in the country.

V. SYSTEM SIZING CALCULATIONS

5.1 PV Array Sizing

Using the worst-case insolation (PSH_{min}) of 3.24 hours and load (E_d) of 7,000 Wh/day

$$P_{PV} = \frac{E_d}{PSH_{min} \times \eta_{sys}} = \frac{7000}{3.24 \times 0.70} \approx 3.086 \text{ Watts}$$

Where:

- E_d = 7000 Wh/day (daily energy demand)
- PSH_{min} = 3.24
- hours (worst-month Peak Sun Hours for Port Harcourt)
- η_{sys} = 0.70 (system efficiency = 70%)

Applying a safety margin of 1.3: Selected Array: 4.4 kWp (8 × 550W Monocrystalline Panels).

5.2 Battery Bank Sizing

Designed for 2 days of autonomy (N_{out}) at 80% Depth of Discharge (DoD) using Lithium batteries:

$$C_{BAT} = \frac{E_d \times N_{out}}{DoD} = \frac{7000 \times 2}{0.8} = 17,500 \text{ Wh}$$

Selected Bank: 20 kWh (4 × 5kWh 48V LiFePO4 Rack-mounted units)

VI. TECHNO-ECONOMIC ANALYSIS

6.1 Cost Comparison: Solar PV vs. Diesel Generator

A comparative analysis was conducted over a 5-year period. While the generator is cheaper initially, the operational costs (fuel + maintenance) escalate rapidly.

- Solar CAPEX: ₦8,040,000 (approx. \$5,300)
- Diesel CAPEX: ₦1,500,000 (approx. \$1,000)
- Diesel OPEX: ₦12,264,000/year (based on ₦1,400/Liter).

Figure 4 illustrates the cumulative expenditure. The crossover point (break-even) occurs in less than one year.

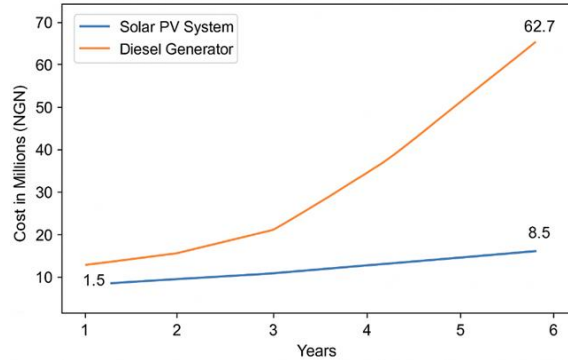


Figure 4: Cumulative Cost Analysis (5-Year Projection)

The graph shows that Solar PV has a high initial cost but remains almost flat over 5 years. Diesel generators start cheap but their cost rises sharply each year due to fuel and maintenance. By Year 5, diesel reaches over ₦60 million while solar stays around ₦8.5 million. Overall, solar is far more economical long-term compared to diesel.

6.2 Economic Results

- Payback Period: < 1 Year.
- 5-Year Savings: > ₦50 Million.
- LCOE (Solar): ~\$0.14/kWh.¹⁷
- LCOE (Diesel): > \$0.60/kWh.

VII. CONCLUSION

This study confirms that a 4.4 kWp / 20 kWh standalone solar system is the technically viable and economically superior solution for powering rural Primary Health Centers in Nigeria. The design ensures 24/7 reliability for vaccine preservation, even during the "August break" monsoon season in southern Nigeria. The transition to LiFePO₄ batteries is critical, offering a lifecycle cost that fossil fuel generators cannot compete with, especially given current fuel inflation rates.

REFERENCES

[1] O. S. Ohunakin, M. S. Adaramola, O. M. Oyewola, and R. O. Fagbenle, "Solar energy applications and development in Nigeria: Drivers and barriers," *Renewable and Sustainable Energy Reviews*, vol. 32, pp. 294–301, Apr.

2014.

[2] Heinrich Böll Stiftung, "Improving Access to Clean Reliable Energy for Primary Health Care Centres in Nigeria," Heinrich Böll Foundation, Abuja, Nigeria, Rep., 2018.

[3] Sustainable Energy for All (SEforALL), "Powering Healthcare: Nigeria Market Assessment and Roadmap," SEforALL, Vienna, Austria, Rep., Mar. 2022. [Online]. Available: <https://www.seforall.org>.

[4] World Health Organization, "Introducing solar-powered vaccine refrigerator and freezer systems: A guide for managers in national immunization programmes," WHO, Geneva, Switzerland, 2015.

[5] A. S. Sambo, "Strategic developments in renewable energy in Nigeria," *International Association for Energy Economics*, vol. 23, pp. 15–19, 2009.

[6] L. Olatomiwa, R. Blanchard, S. Mekhilef, and D. Akinyele, "Hybrid renewable energy supply for rural healthcare facilities: An approach to quality healthcare delivery," *Sustainable Energy Technologies and Assessments*, vol. 30, pp. 121–138, Dec. 2018.

[7] Nigerian Building and Road Research Institute (NBRRI), "Solar Radiation Data Base for Nigeria," NBRRI, Lagos, Nigeria, Rep. No. 7, Dec. 1990.

[8] T. C. Chineke and E. C. Igwiro, "Urban and rural electrification: Enhancing the energy sector in Nigeria using photovoltaic technology," *African Journal of Science and Technology*, vol. 9, no. 1, pp. 102–108, 2008.

[9] M. S. Ziegler, D. Mueller, G. Pereira, J. Song, M. Ferrara, Y.-M. Chiang, and J. E. Trancik, "Storage requirements and costs of various electrical energy storage systems for small-scale renewable energy penetration," *Energy & Environmental Science*, vol. 12, no. 9, pp. 2602–2614, 2019.

[10] NASA POWER Project, "Data Access Viewer," National Aeronautics and Space Administration. [Online]. Available: <https://power.larc.nasa.gov>. [Accessed: Nov. 25, 2025].

[11] A. O. Odukwe and S. O. Enibe, "Energy

- resources and reserves in Nigeria," *Solar & Wind Technology*, vol. 5, no. 3, pp. 335–338, 1988.
- [12] J. O. Oladigbolu, Y. A. Al-Turki, and L. Olatomiwa, "Comparative Study and Sensitivity Analysis of a Standalone Hybrid Energy System for Electrification of Rural Healthcare Facility in Nigeria," *Alexandria Engineering Journal*, vol. 60, no. 6, pp. 5547–5565, Dec. 2021.
- [13] R. O. Fagbenle, J. Katende, O. O. Ajayi, and J. O. Okeniyi, "Assessment of wind energy potential of two sites in North-East, Nigeria," *Renewable Energy*, vol. 36, no. 4, pp. 1277–1283, 2011.
- [14] IEEE Standards Association, "IEEE Recommended Practice for Sizing Lead-Acid Batteries for Stand-Alone Photovoltaic (PV) Systems," IEEE Std 1013-2019, 2019.
- [15] T. Ma, H. Yang, and L. Lu, "A feasibility study of a stand-alone hybrid solar–wind–battery system for a remote island," *Applied Energy*, vol. 121, pp. 149–158, May 2014.
- [16] National Bureau of Statistics (NBS), "Automotive Gas Oil (Diesel) Price Watch (August 2024)," NBS, Abuja, Nigeria, Rep., Sep. 2024.
- [17] O. D. Ukoima, E. C. Ekwe, and P. O. Mbamali, "Techno-Economic Analysis of a Hybrid Renewable Energy System for a Rural Community in Nigeria," *Nigerian Journal of Technology*, vol. 39, no. 1, pp. 234–242, 2020.