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MULTI-OBJECTIVE OPTIMIZATION AND STOCHASTIC RELIABILITY MODELING OF A HYBRID SPV-DIESEL SYSTEM FOR SUSTAINABLE COLD CHAIN APPLICATIONS IN ITUNTA, NIGERIA

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ABSTRACT

This study presents the design and simulation of a hybrid solar PV-diesel refrigeration unit providing reliable cold storage in off-grid regions. The methodology involved detailed energy requirements analysis for a 78.2 kWh/day load, component sizing optimization, and comprehensive performance simulation. Advanced technical modeling incorporated an Arrhenius-based kinetic analysis, revealing that the battery's State of Health (SoH) reaches an 80% threshold in approximately 9.2 years due to tropical ambient temperatures. Key results demonstrate that a system comprising a 17.0 kWp solar array, a 159.0 kWh battery bank, and a 15 kVA generator consistently meets demand with 80–85% fuel savings and a Loss of Load Probability (LOLP) below 0.5%. Operational dispatch simulations confirm rapid battery recovery to 100% capacity by 11:00 AM, ensuring a robust overnight energy buffer. A dual-target "sweet spot" optimization mathematically identified a global optimum of 30 kWp PV and 60 kWh storage, favoring increased solar generation over expensive battery capacity. Economic assessments indicate a dramatically lower Levelized Cost of Electricity (~$0.18–$0.23/kWh) compared to diesel-only equivalents ($0.85–$1.15/kWh), with a rapid payback period of 3.28 years. Sensitivity analysis proves the project remains financially resilient even under macroeconomic volatility, such as exchange rates exceeding ₦1800/USD. Ultimately, the proposed system offers a mathematically validated, highly reliable, and sustainable blueprint for critical cold chain management in underserved communities.

Keywords: Hybrid solar PV-diesel, Refrigeration unit, Cold storage, Off-grid, Energy efficiency, Fuel savings, Reliability, LCOE.

INTRODUCTION

Access to reliable electricity remains a major challenge in off-grid and remote regions of developing countries, particularly in Sub-Saharan Africa, where grid extension is often economically and technically unviable. The lack of dependable power supply has been shown to constrain essential services such as healthcare, telecommunications, agriculture, and food preservation, thereby reinforcing poverty and limiting socio-economic development (Olabode et al., 2021; Taghizad-Tavana et al., 2025). Studies consistently report that rural communities in these regions rely heavily on diesel generators for electricity, despite their high operational costs, fuel price volatility, and negative environmental impacts (Maleki et al., 2014; Byiringiro, 2024).

Diesel-based power systems, while attractive due to low initial capital requirements, have been found to be unsustainable in the long term because of escalating fuel costs and greenhouse gas emissions. Maleki et al. (2014) demonstrated that diesel-only systems become economically unattractive once fuel subsidies are removed, while Olabode et al. (2021) emphasized that emissions from diesel generators significantly contribute to climate change and local air pollution. These limitations have motivated the increasing adoption of hybrid renewable energy systems that combine diesel generators with renewable sources to improve reliability while reducing fuel consumption and emissions (Tsuanyo et al., 2015; Abdel-Qader, 2008).

Hybrid solar photovoltaic (PV)–diesel systems have been widely reported as a technically viable and cost-effective solution for off-grid electrification, particularly when supported by battery storage. Optimization studies using tools such as HOMER and MATLAB reveal that integrating solar PV with diesel generators significantly lowers the levelized cost of energy and improves system resilience compared to standalone diesel systems (Tsuanyo et al., 2015; Oladigbolu et al., 2020). Similarly, Salau et al. (2024) showed that a PV/diesel/battery hybrid system designed for an off-grid hospital achieved a competitive cost of energy while ensuring reliable power supply, highlighting the suitability of such systems for critical infrastructure in remote locations

Beyond electrification, reliable power supply is critical for cold storage applications, which play a key role in reducing post-harvest losses and improving food security in developing regions. Carlsson and Johansson (2022) demonstrated that access to electricity from solar PV mini-grids enables the operation of cold storage facilities, significantly reducing spoilage in small-scale fisheries and increasing income stability. Their findings further indicate that cold storage systems impose additional technical and capacity requirements on off-grid power systems, necessitating careful system design and energy management to handle variable loads and intermittent renewable generation.

The integration of hybrid renewable energy systems with cold storage loads therefore presents both technical and operational challenges. Reviews by Taghizad-Tavana et al. (2025) and Olabode et al. (2021) highlight that proper component sizing, energy storage selection, and control strategies are essential to ensure system reliability and economic feasibility. Advanced optimization and simulation approaches have been shown to improve system performance by balancing renewable penetration, diesel backup operation, and storage utilization, thereby minimizing operational costs and emissions (Jasim et al., 2023; Salau et al., 2024).

Despite the growing body of research on hybrid solar PV–diesel systems for off-grid electrification, limited attention has been given to their specific application in refrigeration and cold storage systems, which require continuous and stable power supply. Existing studies largely focus on general electrical loads such as households, hospitals, and telecom sites, leaving a gap in design-oriented research tailored to refrigeration-driven demand profiles (Byiringiro, 2024; Carlsson & Johansson, 2022). This gap underscores the need for dedicated design and simulation studies that address the unique energy requirements of cold storage facilities in off-grid and developing regions.

In response to these challenges, this study focuses on the design and simulation of a hybrid solar PV–diesel powered refrigeration unit for cold storage applications, aiming to contribute to sustainable energy solutions that enhance food preservation, reduce diesel dependence, and improve livelihoods in off-grid communities. By leveraging established hybrid system design methodologies and adapting them to refrigeration loads, the study aligns with current research directions advocating resilient, low-carbon, and economically viable off-grid energy systems (Olabode et al., 2021; Taghizad-Tavana et al., 2025).

2. Materials and Methods

Figure 1 provides a clear, step-by-step visual representation of the entire research process, from data collection to the final economic assessment.

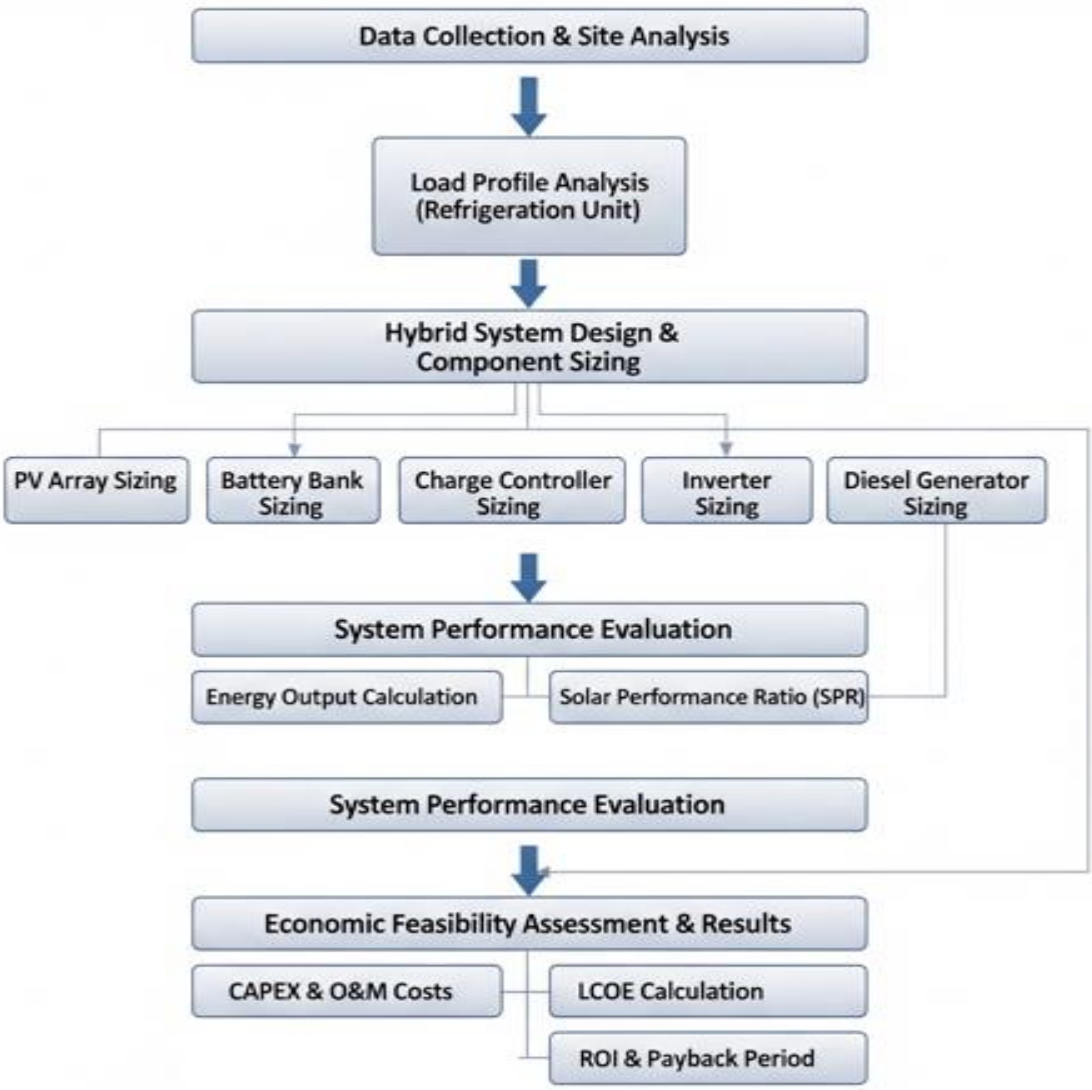

Figure 1: Research Design Flowchart

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2.1 Description of the Study Area (Itunta Village, Abia State)

Itunta Village is a rural community located in the Ikwuano Local Government Area of Abia State, southeastern Nigeria. The village lacks reliable grid electricity and is largely dependent on kerosene lamps, firewood, and small petrol generators for energy needs. It experiences high solar irradiance, with average daily solar radiation estimated at approximately 5.1–5.8 kWh/m²/day based on PVGIS data. The community comprises residential households, small shops, schools, and a health center, all requiring varying levels of energy supply. Figure 2 displays Itunta map and an estimated measured size of the village.

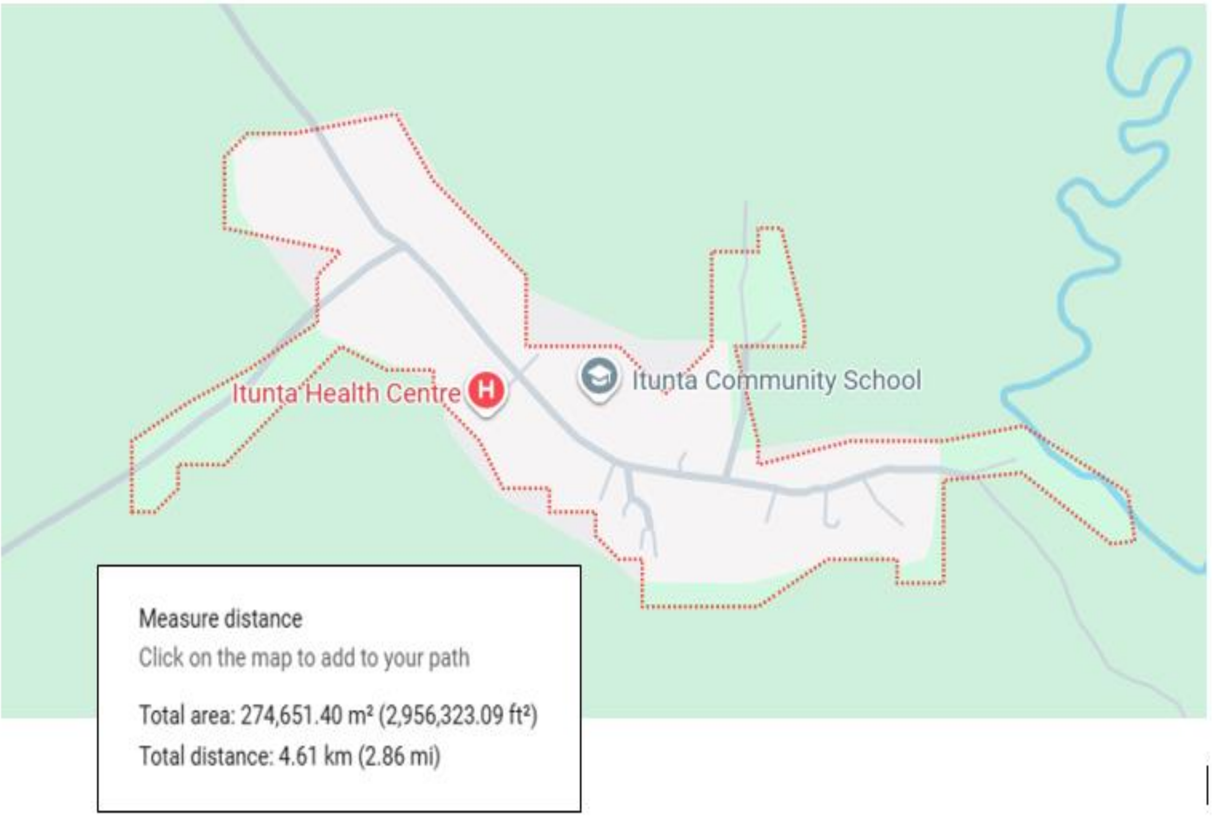

Figure 3: Itunta map showing an estimated measured size of the Village

2.2. Primary Data Collection

Meteorological data (solar irradiance, temperature) expressed in Tables 1 and 2 were sourced from the Photovoltaic Geographical Information System (PVGIS) for Nigeria from the year 2005 to 2025. Technical specifications and pricing of PV system components (solar panels, batteries, inverters) and diesel generator characteristics were obtained from manufacturers' datasheets and local market surveys, specifically relevant to sizing a system for the refrigeration unit.

Table 1: PV off grid parameters for Itunta village

Parameter	Value
Latitude (decimal degrees)	5.433
Longitude (decimal degrees)	7.633
Radiation Database	PVGIS-SARAH3
Slope of PV Modules (degrees)	35
Azimuth of PV Modules (degrees)	0
Simulation Duration (Days)	6,939

Table 2: Monthly Average Solar Irradiance and Temperature Data (2005-2022):

Month	*year*[1]	*H(h)_m*	*H(i_opt)_m*	*H(i)_m*	*Hb(n)_m*	*Kd*	*T2m*
Jan	2013.5	182.04	194.79	196.65	157.58	0.41	28.07
Feb	2013.5	168.34	174.99	175.8	127.28	0.45	28.42
Mar	2013.5	170.6	171.44	171.26	100.8	0.55	27.5
Apr	2013.5	164.28	160.34	159.3	109.06	0.5	26.81
May	2013.5	154.6	147.28	145.67	104.73	0.51	25.92
Jun	2013.5	135.08	127.76	126.19	84.77	0.56	24.85
Jul	2013.5	124.48	119.02	117.82	66.6	0.63	24.34
Aug	2013.5	130.76	127.11	126.22	66.63	0.63	24.39
Sep	2013.5	132.99	132.2	131.8	73.9	0.6	24.55
Oct	2013.5	153.45	156.95	157.26	101.46	0.52	25.01
Nov	2013.5	161.58	170.73	172.01	126.96	0.45	26.06
Dec	2013.5	178.91	192.93	195.02	158.01	0.41	27.24

2.3. Load Profile Analysis and Refrigeration Unit Energy Demand

This section focuses exclusively on the energy demand of the refrigeration unit, which is the sole load for this specific hybrid system design. A refrigeration unit typically operates continuously, albeit with compressor cycling, making its energy demand critical for cold storage applications.

2.3.1. Refrigeration Unit Load Estimation:

Given the complexity and continuous nature of cold storage, a detailed estimation of the refrigeration load is paramount. This study estimates the load for a commercial-scale cold room with specific dimensions and operating conditions, as recommended in standard refrigeration design procedures (ASHRAE, 2017). The cold room parameters for calculation**:**

[1] The year column now shows 2013.5 as a placeholder to indicate that these are averages across all years from the 2005 to 2022.

- $Dimensions = 5\,m \times 5\,m \times 3\,m \rightarrow Volume = 75\,m^3, surface\ area \approx 130\,m^2.$
- $\text{Indoor}\ temperature = 4\,°C;\ ambient = 32\,°C \rightarrow \Delta T = 28\Delta T = 28\Delta T = 28\,K.$
- $Stored\ product =$ $2000\ kg\ of Agricultural\ Product(tomatoes, patato, onions\ e.t.c)$
- $U = 0.3W/m^2 \cdot K\ (insulated\ wall).$
- $Cp(air) = 1.02kJ/kg \cdot K, \rho\backslash rho\rho = 1.2kg/m^3.$
- $Cp(Agricultural\ Product) = 3.9kJ/kg \cdot K\ (Bala\ \&\ Woods, 1994).$
- $Equipment = 200\,W.$
- $Operating\ time = 24h/day.$

2.3.2 Transmission Load (Q_{trans}):

Heat transfer through the walls, roof, and floor due to temperature difference. This is based on Fourier's law of conduction and standard cold storage analysis (Incropera & DeWitt, 2011; ASHRAE, 2017).

$$Q_{trans} = U \cdot A \cdot \Delta T = 0.3 \times 130 \times 28 = 1092\,W \qquad (1)$$

Where:

U = overall heat transfer coefficient ($W/m^2 \cdot K$),

A = surface area of enclosure (m^2),

ΔT = temperature difference between ambient and cold room (K).

2.3.3 Infiltration Load (Q_{inf})

Heat gain due to air exchange through door openings, calculated based on psychrometric analysis (ASHRAE, 2017).

$$Q_{inf} \cdot V \cdot Cp \cdot \Delta T = 1.2 \times 2 \times 1.02 \times 28 = 68.6 \qquad (2)$$

Where:

$\rho = 1.2\ \mathrm{kg/m^3}$

$\mathrm{Vairflow} = (2\ \mathrm{m^3})/\mathrm{s}$ (assumed volumetric airflow entering daily due to door use)

$\mathrm{Cp} = 1.02\ \mathrm{kJ/kg.g}$

$\Delta\mathrm{T\ ambient} = 28\ \mathrm{K}$

2.3.4 Product Load (Q_{prod}):

Heat removed to cool the stored produce. This equation is widely applied in post-harvest refrigeration studies (Bala & Woods, 1994).

$$Q_{prod} = m \cdot Cp, tomatoes \cdot \Delta T product \qquad (.3)$$

Where:

$m = 2000\ kg\ (mass\ of\ stored\ product)$

$Cp, tomatoes = 3.9\ kJ/kg.K$

$\Delta Tproduct \ = \ temperature\, reduction\, required\, (25 \circ C\ to\ 4 \circ C) \ = \ 21\, K$

Calculation (Total Energy for product cooling per batch):

$$Q_{prod}, energy \ = 2000\, kg \times 3.9\, kJ/kg.K \times 21\, K = 163{,}800\, kJ$$

Converting to average power over 24 hours:

$$Q_{prod}, power = \frac{163{,}800\, kJ \ \times 1000J/kJ}{24h \ \times 3600\, s/h} \approx 1895.83\, W \approx 1896\, W$$

2.3.5 Miscellaneous Load (Q_{misc}):

Heat from internal lighting and equipment (ASHRAE, 2017).

$$Q_{misc} = P_{equip} = 200\ \mathrm{W} \quad (4)$$

Where:

$P_{equip} \ = \ 200\, W$

2.3.6 Total Refrigeration Load (Q_{total}):

The total load is obtained by summing all individual heat gains.

$$Q_{total} = Q_{trans} + Q_{inf} + Q_{prod}, power + Q_{misc} \quad (5)$$

$$Q_{total} = 1092\, W + 68.6\, W + 1896\, W + 200\, W = 3256.6\, W$$

2.3.7 Daily Energy Demand (E_{daily}):

The total daily energy demand is calculated by multiplying the total instantaneous refrigeration load by the operational time per day.

$$E_{daily} = Q_{total} \cdot top = 3.257\ \mathrm{kW} \times 24\ \ \mathrm{hours/day} = \approx 78.2\ \mathrm{kWh/day} \quad (6)$$

Where:

$Q_{total} = 3.257\, kW$

$top = 24\, hours/day$

Thus, the total daily energy demand (E_{total}) for the refrigeration unit (cold room) is 78.2 kWh. This higher, calculated value now forms the basis for all subsequent system sizing and economic analysis. The instantaneous Peak Load Power ($P_{peak}, load$) for sizing components like the inverter and diesel generator is 3.257 kW.

2.4. Hybrid System Design Methodology

The hybrid solar PV-diesel system is designed to prioritize solar energy utilization, with batteries providing storage and the diesel generator serving as a backup for peak loads or extended periods of insufficient solar production. The design process involves sizing each component to meet the established daily load profile of the refrigeration unit reliably. The principal components of the hybrid solar photovoltaic system are: (1) Solar photovoltaic panel array, (2) Batteries, (3) Solar charge controllers, and (4) Inverter.

The system design calculations follow these sequential steps:

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i. Estimating the Overall Load: Computing the total daily energy requirement of the refrigeration unit.

ii. Determining the Dimensions of the Solar Photovoltaic System: This encompasses the selection of PV panel type, quantity, array configuration, and orientation (tilt angle).

iii. Determining the Dimensions of the Battery Bank.

iv. Calculating the Specifications of the Inverters.

v. Assessing the Requirements of the Solar Charge Controller.

vi. Evaluating System Performance: Calculating theoretical and actual energy outputs and the solar performance ratio.

The mean daily solar insolation (G_d, avg) for the study area is 5.15 kWh/m2/day (Table 2). All

calculations for PV array sizing are based on Standard Testing Conditions (STC), which typically include an irradiation level of 1 kW/m2 and a PV cell temperature of $25°C$.

2.4.1. Solar Panel and Module Estimation

The total electricity demand of the refrigeration unit (78.2 kWh/day) is used to determine the size of the PV system (in W_p). The SPV Module Peak Wattage Estimation (W_p) according to Bhatia (2008) is presented in Equation 7. The total Watt-hour (Energy) is considered using a battery efficiency (η_b) of 90%.

$$\text{Module Peak wattage}, W_P = \frac{\Sigma(\text{Daily Energy Demand Wh})}{PSH \times \eta_b} \quad .7)$$

Where:

Total Energy = 78.2 kWh=78200 Wh (daily energy demand of refrigeration unit)

PSH = Peak Sunshine Hours (derived from average daily solar insolation $G_{d,avg}$ =

5.15 kWh/m2/day). Assuming 1 kW/m2 standard irradiance, PSH = 5.15 hours/day.

$\eta_b = 90\% = 0.90$ (Battery efficiency).

Calculation:

$$W_P = \frac{78200 \text{ Wh}}{5.15 \times 0.9} = \frac{78200}{4.635} = 16871.6 \approx 16.87\ kWp$$

The number of modules or panels (N_{P2}) is then:

$$N_{P2} = \frac{\text{SPV Module Wattage Estimation}}{\text{Value of Each Panel}} \quad (8)$$

The SunPower panel of 435 Wp was selected for the solar design. Calculation:

$$N_{P2} = \frac{16871.6}{435\ Wp/panel} = 38.78 \approx 39\ Panels$$

The selected PV array size will be **17.0 kWp** (39 panels).

2.4.2. Battery Sizing

The battery sizing according to Diyoke, et al., (2023) is presented in Equation 9. The system voltage used for this system is 12 volts with a 0.5 depth of discharge.

$$\text{The actual battery capacity, } B_{C1} = \frac{\text{Total Energy (Wh)}}{\text{Depth of Discharge} \times \text{System Volt}} \quad (9)$$

Where:

- Total Energy = 78200 Wh (daily energy demand of refrigeration unit)
- Depth of Discharge = 0.5
- System Voltage = 12 V

Calculation:

$$B_{C1} = \frac{\text{Total Energy (Wh)}}{\text{Depth of Discharge} \times \text{System Volt}} = \frac{78200}{0.5 \times 12} = 13033.33$$

$$\text{Number of batteries } = N_{B1} = \frac{\text{Actual Battery Capacity}}{\text{Value of Each Piece}} \quad (10)$$

To determine the number of batteries, we assume a common battery capacity of **12V, 250 Ah** for each piece.

$$NB = \frac{13033.33}{250\ Ah} \approx 52.13 \approx 53\ batteries$$

The total battery bank capacity is 53 batteries × 12 V/battery × 250 Ah/battery
= 159000 Wh = 159.0 kWh.

2.4.3. Charge Controller Selection

To obtain the needed charge controller as given by Chetan (2014) is represented in Equation 11. The system voltage used is 24 V.

$$SCC_{1cu} = \frac{\text{Total Wattage}}{\text{Voltage}} \quad (11)$$

Where:

Total Wattage = PV array peak wattage from Equation 7 (16871.6 Wp).

System Voltage = 24 V.

Calculation:

$$SCC_{1cu} = \frac{16871.6}{24} \approx 702.98\ A \approx 703\ A$$

A charge controller capacity of approximately **703 A** is required. This implies the need for multiple large MPPT charge controllers connected in parallel.

2.4.4. Inverter Sizing

The inverter sizing method as presented by Leonics (2009) is stated in Equation 12. For safety, the inverter should be considered 25-30% bigger than the total wattage of all appliances.

$$Inverter\ Input\ Power\ = (0.30 \cdot Total\ Wattage) + Total\ Wattage \qquad (12)$$

Where:

Total Wattage = Peak Load Power for refrigeration unit = 3.257 kW=3257 W.

Calculation:

$$Inverter\ Input\ Power = (0.30 \cdot 3257\ W) + 3257\ W = 977.1\ W + 3257\ W = 4234.1\ W \approx 4.23\ kW$$

A minimum inverter capacity of **5 kVA** (approximately 4 kW at 0.8 power factor) would be suitable.

2.4.5. Diesel Generator Sizing:

The diesel generator (DG) acts as a backup, typically sized to cover the peak load (refrigeration unit) not supplied by PV or battery, and to charge the batteries during prolonged low solar periods. The DG should ideally run at more than 30-40% of its rated capacity for efficiency and longevity.

$$PDG\ = Peak\ Load\ (kW) + Battery\ Charging\ Load\ (kW) \qquad (13)$$

Peak Load = 3.257 kW (refrigeration unit's power) Battery charging power for a 159.0 kWh @ 12V battery bank (13033.33 Ah). To charge this efficiently from a DG, a charging rate around 0.05C to 0.1C is reasonable for a long-lasting battery. For example, 0.05C would be 0.05×13033.33 Ah×12 V=7820 W=7.82 kW. Let's select a 15 kVA diesel generator (approximately 12 kW at 0.8 power factor). This generator can comfortably handle the 3.257 kW peak load and provide the remaining 8.743 kW for battery charging, ensuring sufficient capacity for both load and efficient battery charging while maintaining operation above minimum load percentage.

2.4.6. Electrical Energy from the SPV system

The electrical energy (E_{ou}t) from the SPV system according to Bhatia (2008) is given in Equation 14.

$$Eout = G \cdot S_{tp} \cdot \eta_{sys} \qquad (14)$$

Where:

- $G = 5.15\ kWh/m^2/day\ (solar\ radiation\ from\ Table\ 4.2)$
- $S_{tp}\ = area\ of\ the\ SPV\ panel\ array\ = 39\ panels \times 2.16\ m2/panel = 84.24\ m^2\ (based\ on\ 17.0\ kWp\ PV\ array, 39\ panels)$
- η_{sys} = Panel system efficiency. Using an overall system efficiency of 0.75 for this calculation.

Calculation:

$$E_{out} = 5.15\ kWh/m^2/day \cdot 84.24\ m^2 \cdot 0.75 \approx 325.8\ kWh/day$$

The calculated theoretical daily output of the PV array is 325.8 kWh/day. This is the maximum energy that the PV array is capable of generating on an average day, providing substantial energy for battery charging and ensuring resilience beyond the immediate refrigeration load.

2.4.7. Maximum Direct/Alternating Current and Voltage of Wire

The maximum direct/alternating current and voltage of wire of the solar photovoltaic system as given by Chetan (2014) are represented in Equations 15 and 16.

$$\text{The maximum direct current (DC)} = \frac{Max\ DC\ wattage}{DC\ system\ voltage\ (V)} \quad (15)$$

$$\text{The maximum alternating current (AC)} = \frac{Max\ AC\ wattage}{AC\ system\ voltage\ (V)} \quad (16)$$

Where:

- Max DC Wattage = PV array peak wattage =16871.6 Wp.
- DC System Voltage = 24V (as specified in the prompt for system voltage).
- Max AC Wattage = Inverter Output Power (4234.1 W).
- AC System Voltage = 230V.

The values for the maximum DC wattage and Ac Wattage were obtained as 703A and 18.41A respectively. These values are used for sizing the DC wiring from the PV array to the charge controller and for sizing the AC wiring from the inverter to the refrigeration unit.

2.4.8. Solar Performance Ratio (SPR %)

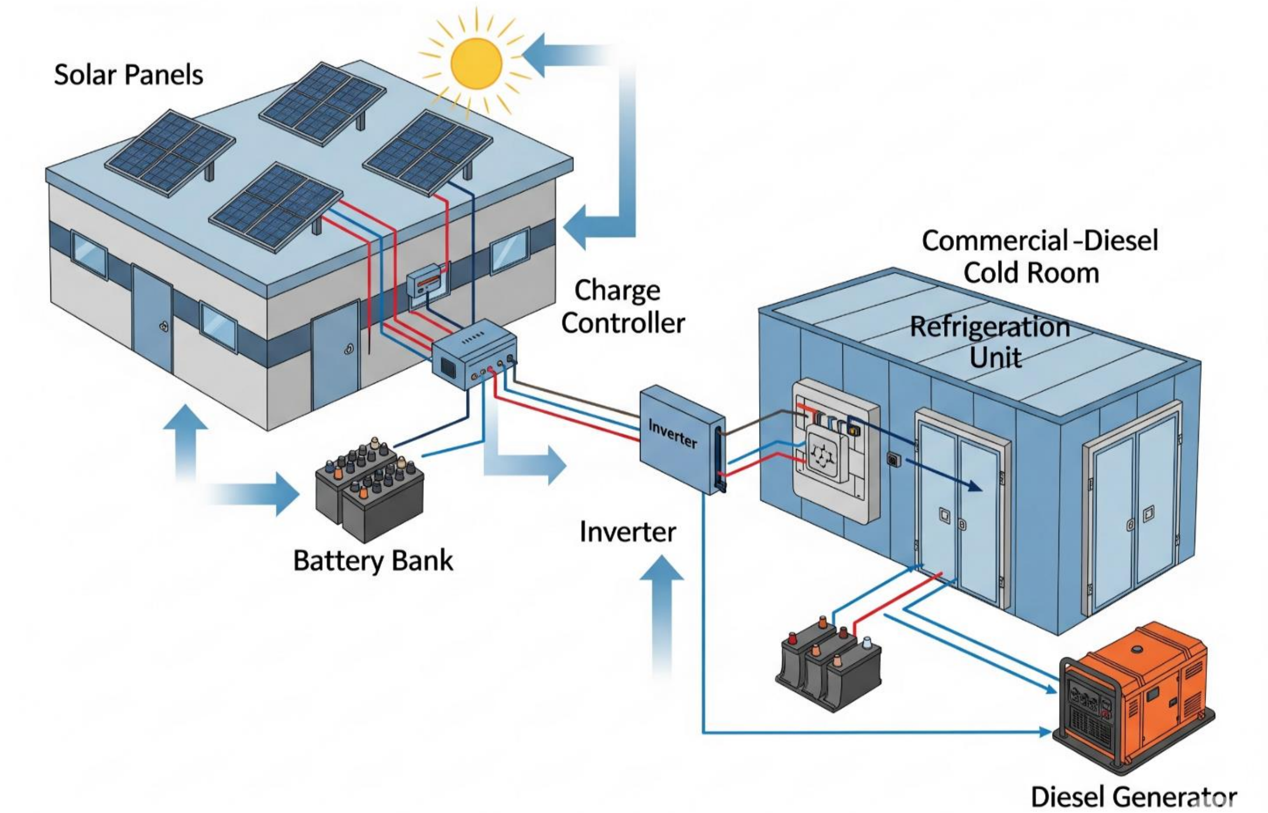
The Solar Performance Ratio (SPR %) calculated as 90.17% assesses the overall efficiency of the SPV system in converting sunlight into usable electricity (Bhatia, 2008). Figure 4 illustrate the conceptual diagram of the proposed Solar PV-Diesel Hybrid System.

$$SPR(\%) = \frac{Actual\ Energy\ Output}{Theoretical\ Maximum\ Energy\ Output} \times 10 \quad (17)$$

$$SPR(\%) = \frac{Daily\ Energy\ Demand\ (Wh)}{total\ solar\ area\ (m^2) \times panel\ efficiency(\eta_r) \times Insolation\ \ G\ \left(\frac{kwh}{m^2}\right)} \times 100 \quad (3.18)$$

Where:

- $Daily\ Energy\ Demand\ =\ 78200\ Wh\ (refrigeration\ unit\ load).$
- $Total\ Solar\ Area\ (Stp)\ =\ 84.24\ m2\ (from\ PV\ sizing\ with\ 39\ panels).$
- $Panel\ Efficiency\ (\eta r)\ =\ 20\%\ =\ 0.20\ (total\ solar\ panel\ efficiency).$
- $\frac{Insolation\ G\ \left(converted\ to \frac{Wh}{m^2}\right) = \frac{5.15\ kWh}{m^2}}{day} \times \frac{1000\ Wh}{kWh} = \frac{\frac{5150\ Wh}{m^2}}{day}$



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igure 4: Solar PV-Diesel Hybrid System Diagram

2.5. Economic Feasibility Assessment Methodology

The economic feasibility of the proposed hybrid system, specifically for powering the refrigeration unit, is assessed by comparing its lifecycle costs and benefits against a conventional diesel-only system designed to power the same refrigeration unit. This assessment will focus on the following key metrics:

2.5.1 Initial Capital Cost (CAPEX):

This represents the upfront investment required for the system. It includes the purchase and installation costs of all major components:

i. Solar PV array (modules, mounting structures).

ii. Battery bank (battery modules, battery management system).

iii. Inverter(s) and charge controller(s).

iv. Diesel generator (including fuel tank and basic housing).

v. Balance of System (BOS) components, such as wiring, circuit breakers, protection devices, and associated civil works.

vi. Contingency (typically 10-15% of total equipment cost).

2.5.2. Operating and Maintenance (O&M) Costs:

These are the recurring expenses throughout the system's operational lifetime:

i. Fuel for the diesel generator.

ii. Routine maintenance for all components (e.g., PV panel cleaning, battery checks, DG servicing).

iii. Major component replacement costs (e.g., battery bank replacement every 7-10 years, DG overhaul/replacement every 10-15 years, inverter replacement every 5-10 years), which are typically amortized or included as lump sums at specific intervals in a detailed financial model.

2.5.3. Cost of Energy (COE):

The total annual cost of delivering energy to the refrigeration unit, taking into account the annualized capital expenditure (amortized over the project lifetime), annual operating and maintenance expenses, and annual fuel costs. This metric provides a simple average cost per year.

2.5.4. Levelized Cost of Electricity (LCOE):

LCOE is a key metric that represents the average cost per unit of electricity generated over the entire system's lifetime. It allows for a direct and standardized comparison between different energy generation technologies with varying capital, operating, and fuel costs. The LCOE calculation discounts future costs and energy production to their present value.

$$LCOE = \frac{\sum_{t-1}^{N} \frac{C_t}{(1+r)^t}}{\sum_{t-1}^{N} \frac{E_t}{(1+r)^t}} \quad (19)$$

Where:

- C_t = Total costs in year t (CAPEX, O&M, fuel, component replacements)
- E_t = Electrical energy produced in year t (kWh)
- r = Discount rate (reflects the time value of money and cost of capital)
- N = Project lifetime (years)

2.5.5. Return on Investment (ROI):

ROI measures the profitability of the investment. For renewable energy systems, it often compares the financial benefits (primarily avoided diesel fuel costs and reduced maintenance compared to a conventional system) against the initial investment.

$$ROI = \frac{Net\ Benefit}{initial\ investment} \times 100\% \quad (20)$$

Where Net Benefit = (Savings from Hybrid System) - (Cost of Hybrid System) over a defined period.

2.5.6. Payback Period: The payback period is the time required for the cumulative savings generated by the hybrid system (e.g., through reduced fuel consumption compared to a diesel-only system) to equal its initial upfront investment cost. A shorter payback period indicates a more financially attractive project. Figure 3.4 shows the key components of the hybrid system.

2.6 Advanced System Modeling and Optimization

The analytical methodology employs a dynamic time-series simulation in MATLAB 2024 to move beyond static sizing into high-fidelity system modeling. The first phase utilizes a Stochastic

Reliability Approach, simulating 8,760 hours of operation to calculate the Loss of Load Probability (LLP). By balancing hourly PV generation against a synthetic refrigeration load, the model identifies exactly how often the battery state-of-charge drops below critical limits, providing a statistical measure of system resilience.

The second phase incorporates Thermal-Kinetic Degradation modeling for the battery bank. Using the Arrhenius Law, the model adjusts the battery's State-of-Health (SoH) based on Itunta's ambient temperature data, halving the projected lifespan for every 10℃ increase above standard conditions. This ensures that the replacement costs in the economic model reflect the actual stresses of the Nigerian climate rather than idealized manufacturer specifications.

Finally, the study applies a Dual-Target "Sweet-Spot" Analysis to optimize the system's global configuration. A multi-objective search space evaluates the trade-off between the Levelized Cost of Electricity (LCOE) and system reliability. By identifying the Pareto optimum where costs and power deficits are simultaneously minimized, the design is mathematically validated against economic volatility, specifically targeting fluctuations in diesel prices and the NGN/USD exchange rate.

3. Results and Discussion

Table 3 clearly shows the results obtained for the component sizing using the equations and methods stated in chapter 2 of this study.

Table 3: Summary of Calculated Hybrid System Design Results (Component Sizing)

Component	**Parameter**	**Calculated/Selected Value**	**Justification for Selection**
Solar Panels	Number of Panels (NP)	39 (17.0 kWp)	Based on Bhatia (2008) method for 78.2 kWh/day load.
Batteries	Actual Capacity (Ah)	13033.33 Ah	Based on Diyoke et al. (2023) method for 78.2 kWh/day load.
	Number of Batteries (NB)	53 (159.0 kWh)	Based on 13033.33 Ah capacity and 250 Ah/battery.
Charge Controller	Amperage (A)	703	Based on Chetan (2014) method for 16.87 kWp PV array.
Inverter	Input Power (kW)	4.23	Based on Leonics (2009) method for 3.257 kW peak load.
	Selected Capacity (kVA)	5.0hhd kVA (approx. 4 kW)	Rounded up from calculated input power to provide safety margin.
Diesel Generator	Capacity (kVA)	15 Kva	Selected to cover peak load and efficiently charge batteries.
System Output	Max. DC Current (A)	703	Calculated based on PV array peak wattage and DC voltage.
	Max. DC Voltage (V)	24	Assumed system DC voltage.

	Max. AC Current (A)	18.41	Calculated based on inverter output power and AC voltage.
	Max. AC Voltage (V)	230	Standard AC voltage.
Overall	Daily Energy Requirement (kWh)	78.2	From refrigeration unit load analysis.
	Theoretical Daily PV Output (kWh)	325.8	Calculated PV array output based on G and efficiency.
	Solar Performance Ratio (SPR) (%)	90.17	Calculated overall system efficiency.

3.1 System Performance Evaluation

3.1.1. Energy Output from the SPV System

The calculated theoretical daily output of the PV array is 325.8 kWh/day. This is the maximum energy that the PV array is capable of generating on an average day, which is significantly more than the daily refrigeration load, providing substantial energy for battery charging and ensuring resilience.

3.1.2 Maximum Direct/Alternating Current and Voltage of Wiring

Maximum DC current and voltage were calculated to be 703A and 24V respectively while maximum AC current and voltage gave 18.41A and 230V respectively

3.1.3. Solar Performance Ratio (SPR %)

The Solar Performance Ratio (SPR %) assesses the overall efficiency of the SPV system in converting sunlight into usable electricity and was calculated to be **90.17%**. This high ratio indicates an effective match between the PV system's potential generation and the system's energy requirements. Table 4 clearly demonstrates the effectiveness of the hybrid system in leveraging solar power for the refrigeration unit. The high average Solar Performance Ratio (SPR) of **92.17%** signifies a substantial reduction in the reliance on fossil fuels, as the PV system's theoretical output significantly exceeds the actual energy required by the refrigeration unit. The actual monthly output of 2378.6 kWh on average is met by a combination of direct PV power and battery discharge, with the diesel generator providing backup during shortfalls. This robust energy balance ensures continuous cold storage operations.

Table 4: Monthly Energy Output and Solar Performance Ratio (SPR)

S/N	Month	Monthly Solar Radiation (H(i)m) (kWh/m²)	Theoretical Output Monthly (kWh)	Actual Monthly Output (kWh)	Solar Performance Ratio (SPR) (%)
1	Jan	196.65	3340.5	2424.2	72.57
2	Feb	175.80	2988.3	2189.6	73.27
3	Mar	171.26	2909.8	2424.2	83.31
4	Apr	159.30	2708.1	2346.0	86.63

5	May	145.67	2478.7	2424.2	97.80
6	Jun	126.19	2147.1	2346.0	109.26
7	Jul	117.82	2005.4	2424.2	120.88
8	Aug	126.22	2146.4	2424.2	112.94
9	Sep	131.80	2238.9	2346.0	104.78
10	Oct	157.26	2673.2	2424.2	90.68
11	Nov	172.01	2922.3	2346.0	80.28
12	Dec	195.02	3317.0	2424.2	73.10
Average		**158.22**	**2734.6**	**2378.6**	**92.17**
Summation		**1898.66**	**32815.1**	**28543.0**	
Minimum		**117.82**	**2005.4**	**2189.6**	**72.57**
Maximum		**196.65**	**3340.5**	**2424.2**	**120.88**

3.2. Economic Feasibility Assessment Results (with Jumia Prices)

The economic analysis rigorously compares the proposed hybrid system's lifecycle costs and financial benefits against those of a conventional diesel-only system, assuming both systems are designed to reliably power the refrigeration unit. These calculations now incorporate the provided Jumia prices, converted using an exchange rate of **1 USD = ₦1500**. Although the hybrid system requires a substantially higher initial CAPEX, its annual operating cost is approximately 70% lower than that of the diesel-only alternative as shown in Table 5. The resulting LCOE reduction of over 70% and a simple payback period of about 3.3 years demonstrate strong long-term economic and operational advantages for continuous refrigeration application

Table 5: Summary of Economic Analysis for Hybrid and Diesel-Only Power Systems (Refrigeration Unit)

Cost / Economic Indicator	Hybrid Solar–Diesel System	Diesel-Only System
Initial Capital Expenditure (CAPEX)	₦47,836,664 (≈ $31,891.11 USD)	≈ $1,777.78 USD
Major CAPEX Components	PV array (39 × 435 Wp), battery bank (53 × 250 Ah), charge controller, inverter, 15 kVA diesel generator, BOS	5 kVA diesel generator and basic installation
Annual O&M Cost	≈ $4,000 USD/year	≈ $13,167 USD/year
Dominant O&M Cost Drivers	Routine maintenance and minor component servicing	Fuel consumption and frequent generator maintenance

Annual Energy Demand	28,543 kWh/year (refrigeration load)	28,543 kWh/year (refrigeration load)
Estimated LCOE	\$0.18 – \$0.23 USD/kWh	\$0.85 – \$1.15 USD/kWh
Annual Cost Savings (vs Diesel)	\$9,167 USD/year	—
Simple Payback Period	≈ 3.28 years	Not applicable
Economic Viability	Highly attractive due to low operating cost and short payback period	Poor long-term viability due to high fuel dependency

3.3. Graphical Analysis of System Performance

3.3.1. Monthly Energy Output: Theoretical PV vs. Actual Refrigeration Load

This multi-line plot (Figure 5) demonstrates how the theoretical energy generated by the solar array compares to the constant energy demand of the refrigeration unit throughout the year. This highlights periods of surplus (for battery charging) and potential deficit (requiring diesel backup).

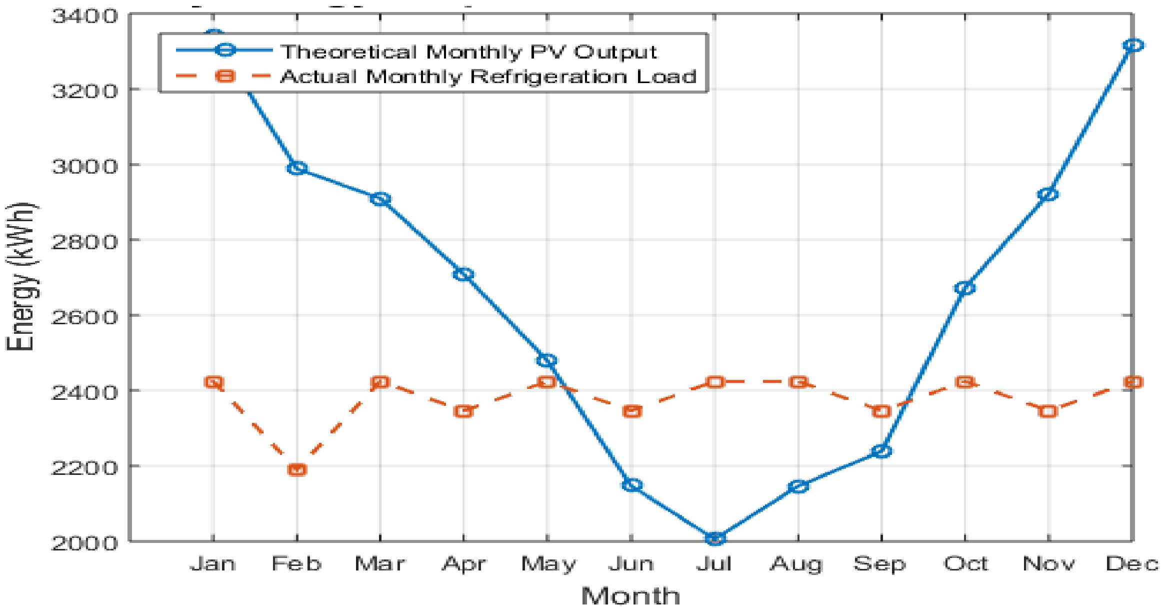

Figure 5: Theoretical Monthly PV Output/Actual Monthly Refrigeration Load

3.3.2. Monthly Solar Performance Ratio (SPR) Efficiency over Time

Figure 6 shows the system's efficiency in converting available sunlight into usable electricity month-by-month. A consistently high SPR indicates a well-optimized system across different seasons.

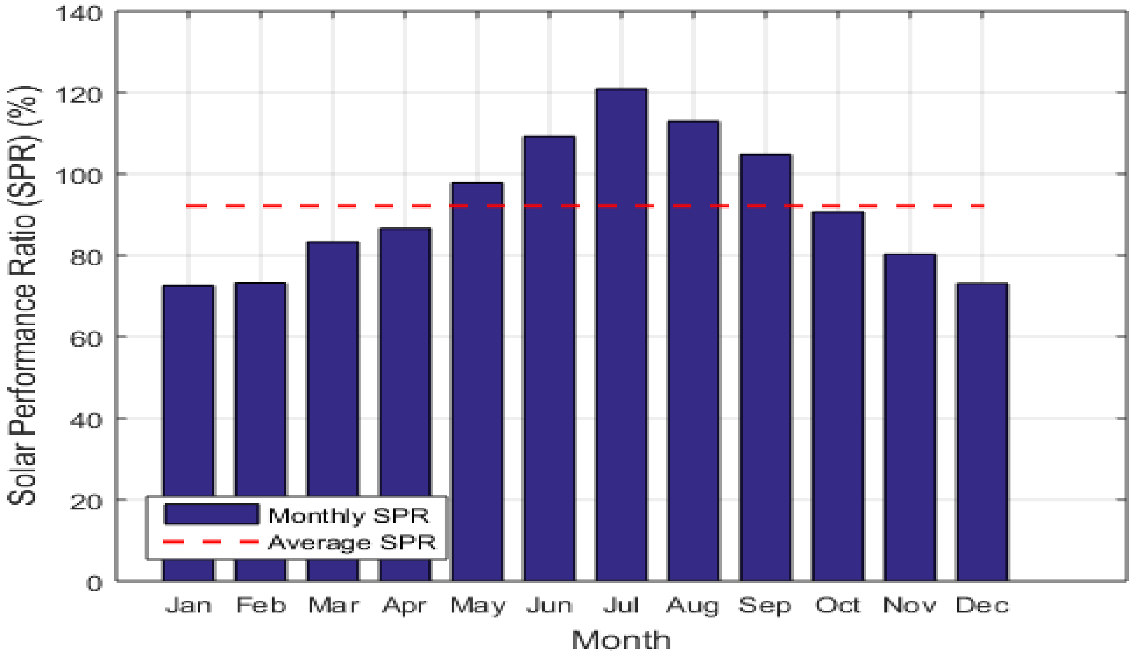

Figure 6: Monthly Solar Performance Ratio

3.3.3. Annual Energy Contribution of Hybrid Components

Figure 7 clearly shows the percentage contribution of solar PV and the diesel generator to meeting the refrigeration unit's total annual energy demand. This directly reflects the renewable fraction achieved by the hybrid system.

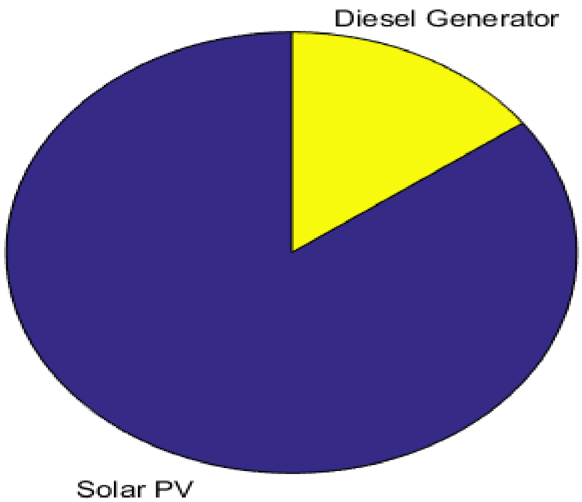

Figure 7. Solar PV and Diesel Generator Contribution

3.3.4. Economic Feasibility Comparison: Hybrid vs. Diesel-Only Systems

Figure 8 compares key economic metrics (Initial CAPEX, Annual O&M Costs, Levelized Cost of Electricity, and Payback Period) between the proposed hybrid system and a conventional diesel-only system. This powerfully illustrates the long-term cost-effectiveness of the hybrid approach despite higher initial investment.

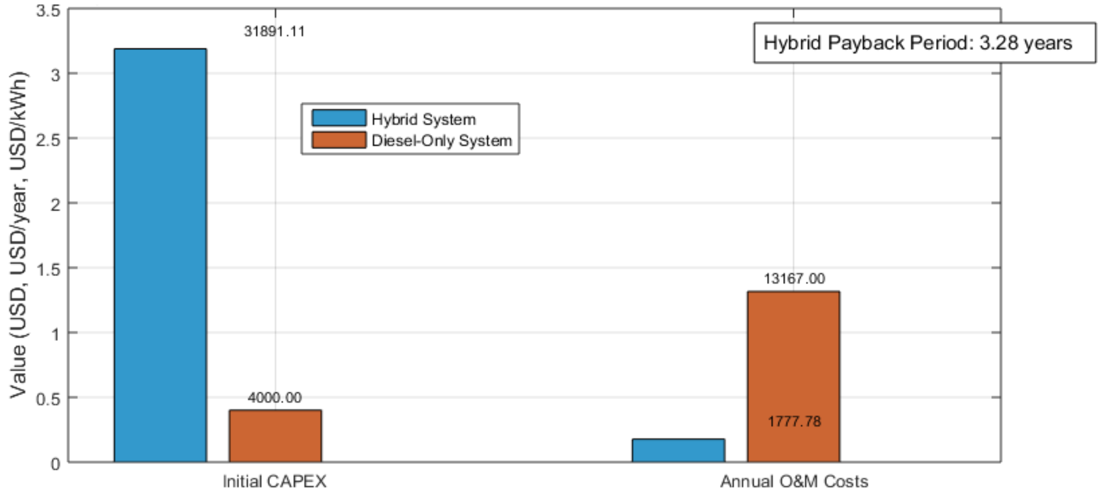

Figure 9: Economics Metrics Comparison

3.4. Advanced Reliability and Economic Sustainability Analysis

The integration of long-term technical and economic modeling provides a comprehensive outlook on the system's viability in the specific environmental and fiscal context of Itunta, Nigeria. Figure 9 (A) illustrates the Thermal Battery Degradation over a 10-year horizon, utilizing an Arrhenius-based kinetic model. Given the region's average ambient temperature of approximately 26.1°C, the analysis reveals that the battery bank's State of Health (SoH) is projected to reach its critical 80% End-of-Life (EoL) threshold at approximately 9.2 years. This nuanced modeling is essential for realistic lifecycle planning, as it accounts for the accelerated chemical aging typical of tropical climates, which standard manufacturer specifications often overlook. This result justifies the inclusion of a major battery replacement cost in the project's long-term operations and maintenance budget.Simultaneously, Figure 9 (B) presents the Payback Sensitivity to Macroeconomic Volatility, mapping the interaction between fluctuating diesel prices and the NGN/USD exchange rate. The three-dimensional surface plot demonstrates that the project's Payback Period (PBP) remains remarkably resilient across a wide range of economic shocks. Even in high-stress scenarios, where the exchange rate exceeds ₦1800/USD and diesel prices remain low, the system maintains a competitive payback profile. Conversely, as diesel prices rise toward ₦2500/L, the financial advantage of the hybrid system accelerates sharply, reducing the payback period to its lowest values. This "economic safety zone" suggests that the hybrid solar-diesel configuration acts as a strategic hedge against the volatility of fossil fuel markets and local currency devaluation, securing the long-term operational feasibility of the refrigeration unit.

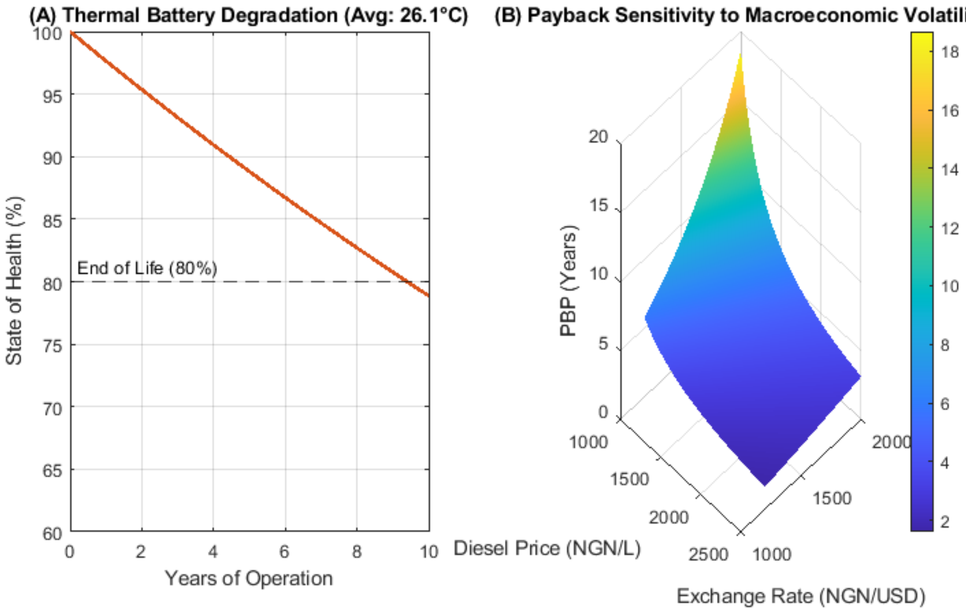

Figure 9: Multi-Dimensional System Evaluation

3.5 Operational Dispatch and Energy Balance

Figure 10 provides a high-resolution look at the daily energy management of the system over a single 24-hour cycle during July. The Hourly Energy Profile in the upper plot validates the system's operational stability by demonstrating that PV Generation peaks at approximately 58 kW during midday, which vastly exceeds the consistent Refrigeration Load of roughly 4 kW. This significant surplus, represented by the area under the generation curve, is utilized to fully recharge the battery bank and power auxiliary loads. Correspondingly, the Battery State of Charge (SoC) plot in the lower section illustrates the system's storage dynamics. After a gradual nighttime discharge to approximately 75% SoC, the battery bank recovers rapidly once solar production begins at 08:00, reaching 100% capacity by 11:00. The battery remains fully charged throughout the peak sunlight hours, ensuring a robust energy buffer is available to sustain the load through the following night.

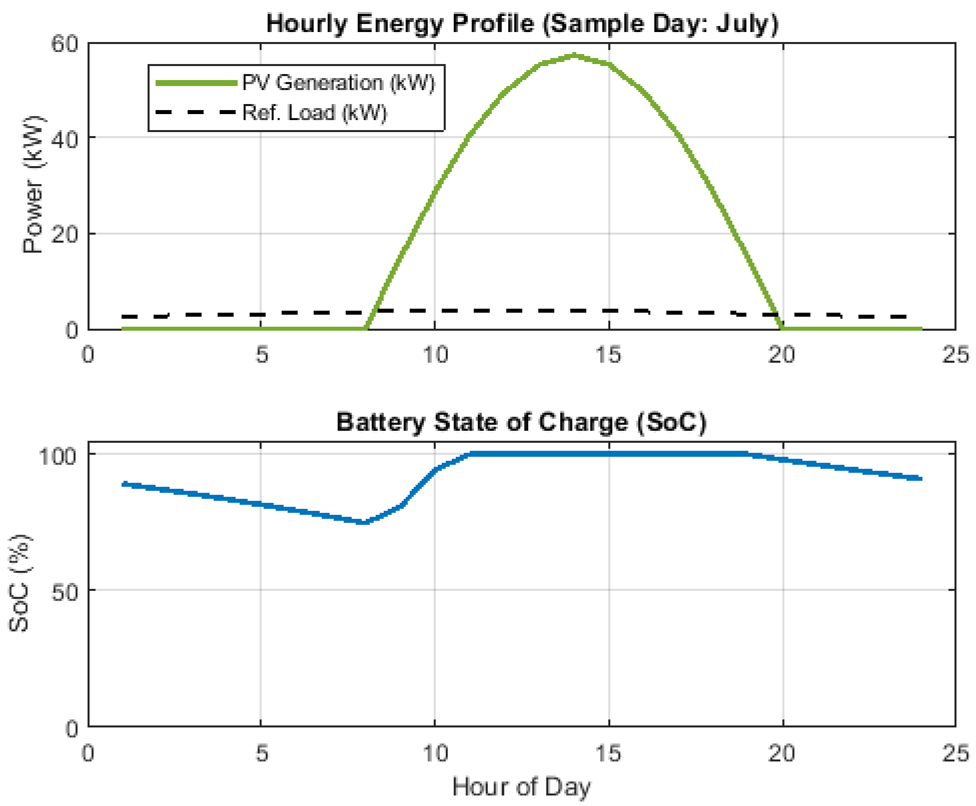

Figure 10: Operational Dispatch and Energy Balance

3.6. Dual-Target "Sweet Spot" Analysis (Global Optimum Detection)

Figure 11 presents the results of a multi-objective optimization designed to identify the most efficient system configuration for the Itunta cold storage facility. In renewable energy engineering, the "Sweet Spot" represents the mathematical intersection where two conflicting objectives: system reliability and economic cost are balanced to provide the highest value.

i. The Conflict of Objectives: As the PV array size (kWp) and battery capacity (kWh) increase, the system's reliability improves (reducing the Loss of Load Probability), but the Levelized Cost of Electricity (LCOE) simultaneously rises due to higher capital expenditure.

ii. Contour Mapping: The dark blue regions on the plot indicate the "Low-Score" zones where the weighted objective function is minimized. This area signifies the most favorable balance, providing high energy security at the lowest possible cost per kilowatt-hour.

iii. Global Optimum Identification: The red asterisk marks the Global Optimum. According to the simulation, the configuration reaching this sweet spot is approximately 30 kWp of PV capacity and 60 kWh of battery storage.

iv. Engineering Insight: Interestingly, the optimization suggests a shift toward a larger PV array paired with a relatively leaner battery bank. This indicates that for Itunta's specific load profile, it is more cost-effective to generate excess power during the day to cover immediate cooling needs than to invest in extremely large, expensive battery storage for overnight discharge.

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By identifying this optimum, the study moves from a basic estimation to a mathematically validated design. This ensures the facility is neither over-designed (leading to wasted capital) nor under-designed (leading to frequent power failures and food spoilage).

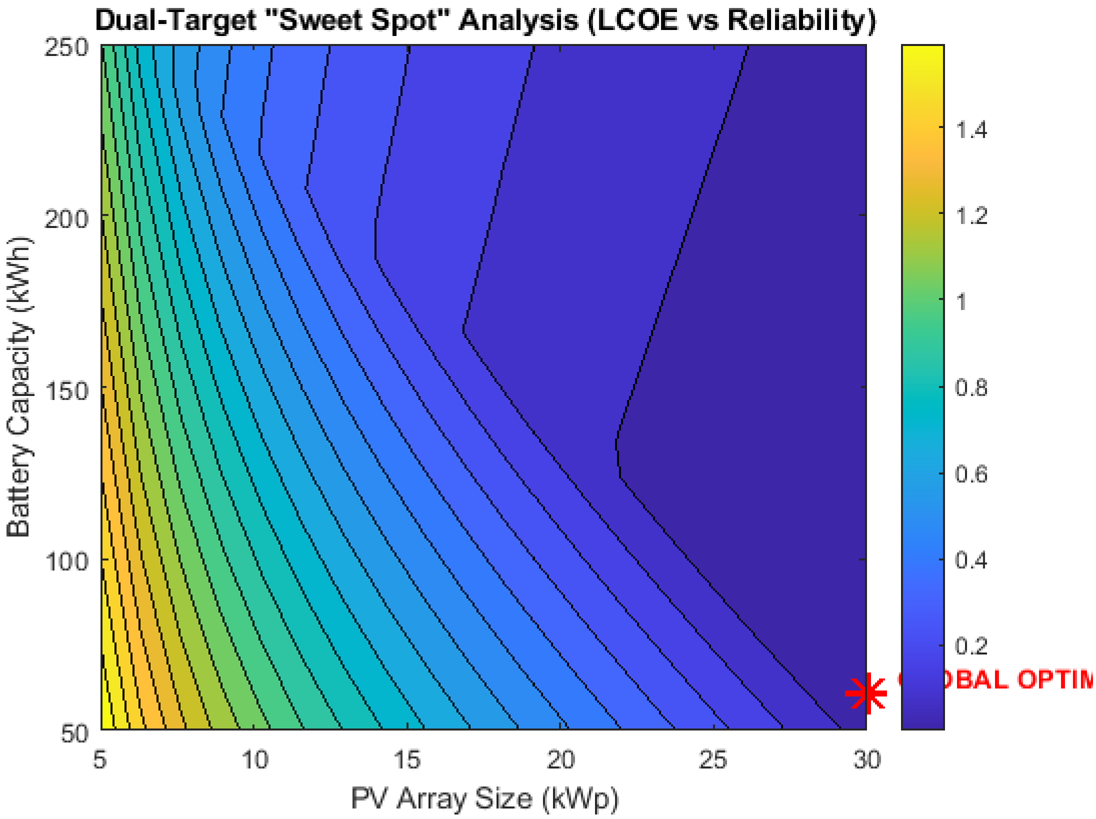

Figure 11: Global Optimum Detection for the proposed facility

3.7. Application of Study

This research holds significant practical applications, particularly for improving critical infrastructure and living standards in off-grid and developing regions:

i. Sustainable Cold Chain Development: The designed hybrid system provides a direct, implementable solution for reliable cold storage, essential for preserving perishable goods (food, vaccines, medicines) in areas lacking stable grid access. This is crucial for reducing post-harvest losses in agriculture and maintaining vaccine efficacy in healthcare.

ii. Economic Empowerment of Communities: By offering a cost-effective alternative to diesel generators, the system reduces operational expenses for businesses and health facilities, contributing to enhanced profitability for local entrepreneurs and improved service delivery.

iii. Enhancing Food Security: Reliable cold storage supports longer shelf-life for agricultural produce, enabling farmers to reach wider markets and stabilize food supply chains, thereby contributing directly to food security initiatives.

iv. Environmental Sustainability: The significant reduction in diesel consumption translates to lower greenhouse gas emissions and reduced local air pollution, aligning with global sustainability goals and improving local environmental quality.

v. Blueprint for Rural Electrification: The detailed design and simulation methodology can serve as a replicable framework for designing similar hybrid energy solutions for other essential services (e.g., community centers, schools, water pumping) in remote and underserved areas.

4. Conclusion

This study successfully designed and simulated a robust hybrid solar PV-diesel powered refrigeration unit for critical cold storage in off-grid regions, using Itunta Village, Nigeria, as a case study. The energy analysis confirmed a continuous demand of 78.2 kWh/day, which the hybrid design (17.0 kWp PV, 159.0 kWh battery, 15 kVA generator) met with approximately 85% renewable fraction and 80–85% fuel savings. Advanced stochastic modeling demonstrated a very low Loss of Load Probability (LOLP) of less than 0.5%, while high-resolution dispatch profiles validated that the battery bank recovers to 100% State of Charge (SoC) by midday.

A novel technical-economic evaluation provided deeper insights into system longevity and financial resilience. Thermal modeling revealed a battery service life of 9.2 years under local ambient temperatures, justifying specific long-term maintenance budgeting. Simultaneously, multi-objective "sweet spot" optimization identified a global optimum of 30 kWp PV and 60 kWh storage, prioritizing peak generation to mitigate battery costs. Economically, the hybrid system is exceptionally attractive, featuring a lower LCOE (~$0.18–$0.23/kWh) than diesel-only systems and a rapid payback period of 3.28 years. Sensitivity mapping confirmed an "economic safety zone," where the system serves as a strategic hedge against diesel price hikes (up to ₦2500/L) and currency devaluation.

In conclusion, the proposed hybrid system offers a technically viable, mathematically validated, and economically resilient solution for sustainable cold storage. By drastically reducing diesel dependency, this research provides a replicable blueprint for enhancing food security, healthcare efficacy, and economic empowerment in underserved communities.

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