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OPTIMAL DESIGN AND OPERATIONAL PERFORMANCE OF A 5 KVA HYBRID SOLAR PHOTOVOLTAIC SYSTEM FOR RESIDENTIAL POWER SUPPLY IN PORT HARCOURT, NIGERIA

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ABSTRACT
This paper presents a design and performance analysis of a 5 kVA hybrid solar photovoltaic (PV) system tailored for residential applications in Port Harcourt, Nigeria. The purpose of this research is to design an optimal solar PV system configuration and rigorously evaluate its technical performance and economic viability through a detailed load assessment of a typical Port Harcourt residence. The PV Syst software was used for the simulation, suitable PV modules (mono 550 Wp), inverters (5kVA), batteries (deep-cycle gel, 12V, 200Ah) and charge controllers (MPPT 150Ah, 48V) were selected for optimal operation. Simulations showed that the annual energy requirement for the Household is 18.56 kWh (6774.4 kWh/day) and the energy available through solar panel is 7675.5 kWh, where the energy supplied to the user is 6099.0 kWh (16.71 kWh/day) a slightly less than the required load, which may be due to some losses. The detailed load assessment revealed total daily energy consumption of 18.21 kWh, including a 20% safety margin, net usable daily energy yield of 18.56 kWh from the 5.5 kWp solar array, effectively meeting the 18.21 kWh daily energy demand, the system offers significant long-term economic advantages by displacing costly generator fuel consumption and maintenance. The system can meet power needs while minimizing energy waste and maximizing solar energy use.

Key words: Energy independence, hybrid Photovoltaic (PV), Performance analysis, PVsyst, Renewable energy.

1.0 INTRODUCTION

The global landscape of solar energy adoption has witnessed unprecedented growth over the past two decades, transforming from a niche technology to a mainstream energy source International Renewable Energy Agency [1]. Driven by declining costs of PV modules, supportive government policies, and increasing awareness of climate change, solar PV capacity has surged worldwide. According to the International Renewable Energy Agency, global installed renewable energy capacity reached approximately 3,870 GW by the end of 2023, with solar PV accounting for a significant portion of this growth, adding 345.5 GW in 2023 alone [1]. Major players in this expansion include China, the European Union, and the United States, which have implemented various incentives such as feed-in tariffs, tax credits, and net metering policies to accelerate deployment [2]. This global trend underscores solar energy's critical role in achieving decarbonization targets and enhancing energy security.

Within the African context, solar energy offers a transformative pathway to address pervasive energy poverty and drive sustainable development. While Africa possesses immense solar resource potential, its actualized PV capacity lag behind other continents [3]. However, significant progress is being made, particularly in countries like South Africa, Egypt, and Morocco, which have developed large-scale solar farms and implemented supportive regulatory frameworks [4]. Nigeria, despite its abundant solar insolation averaging 6.2 kWh/m²/day in some regions, has historically underutilized this resource. The country's energy sector is dominated by a fragile and inefficient national grid, which severely limits industrial growth and daily residential life [5]. The challenges in Nigeria's power sector are multifaceted, encompassing inadequate generation capacity, dilapidated transmission and distribution infrastructure, pervasive technical and commercial losses, and significant governance issues [6]. The recent removal of fuel subsidies has significantly increased the operational costs of petrol and diesel generators this economic shift, coupled with increasing public awareness of sustainable energy benefits, inadvertently making solar PV systems more economically attractive driving a bottom-up adoption of residential and commercial solar solutions, particularly in urban areas like Port Harcourt where grid unreliability is most acute.

This study was set to design, simulate, construct, analyze, and evaluate the performance and economic viability of a 5 kVA hybrid solar electricity system to address the urgent need for a viable and cost-efficient alternative energy solution for residential use in Port Harcourt.

2.0 METHODOLOGY

This study adopted a systematic approach to design, simulate and analyze a 5 kVA hybrid solar PV system for residential use in Port Harcourt, Nigeria. The system designed is to be an on-grid photovoltaic system configuration with back-up batteries with a fixed tilt orientation. There is no solar power injected into the grid since our utility company, PHCN, does not support net metering.

2.1 Study Area Description:

Port Harcourt, situated in the tropical rainforest belt of Southern Nigeria on latitude 4°49′27"N and longitude 7°02′01"E. The city experiences a tropical monsoon climate with an average daily global solar insolation ranging from 3.8 kWh/m²/day to 5.5 kWh/m²/day, averaging around 4.5-5.0 kWh/m²/day annually [7]. This consistent solar resource, combined with prevalent unreliable grid power, makes Port Harcourt an ideal location for evaluating residential solar PV systems.

2.2 PVsyst Simulation Software

PVsyst is a simulation software that was first designed in Geneva and helps in calculating the working and operations of PV system. This software helps in designing the configuration of the system and enable to calculate the amount of energy generated. The output is based on the simulation of the sizing system which further depends on geographical site location of PV system. Results may include several simulation variables that can be displayed in monthly, daily or hourly values. The "Loss Diagram" predicts the weaknesses in the system design [8,9].

Simulation in PV Syst is carried out in the following steps

(i) Defining the project Different sites and meteonorm files are already present in the PVsyst databases but one can create his own project depending on the location of the site and meteonorm files that are to be used.

(ii) Creating a system variant: Calculation version of the project created in step1is created by the user. Module orientation, system configuration and loss parameters are to be defined by the user.

(iii) Running the simulation: Simulation generates different graphs and reports for the PV system. The user can analyze the results in the program, export them to a different program or save the results for further evaluation. [10,11]

2.3 Energy Load Assessment:

A critical initial step was to quantify the energy consumption of a typical three-bedroom residential house in Port Harcourt. This involved identifying all common electrical appliances, their power ratings, and estimating their average daily usage hours. A safety margin of 20% was incorporated into the total daily consumption to account for variations in usage and future expansion. The detailed breakdown of estimated daily energy consumption for typical household appliances is presented in Table 1. The total estimated daily energy consumption, including the safety margin, was determined to be approximately 18.21 kWh. This figure serves as the baseline for all subsequent sizing calculations.

Table 1: Estimated Daily Energy Consumption for a Typical Residential House in Port Harcourt.

S/N	Appliance	Quantity	Power Rating (W)	Daily Usage (Hours)	DailyEnergy Consumption (Wh)
1	LED Bulbs (9W)	10	90	8	720
2	Ceiling Fans	4	240	10	2400
3	Television (LED)	1	100	6	600
4	Refrigerator (Medium)	1	150	24	3600
5	Air Conditioner (1.5 HP)	1	1500	4	6000
6	Water Pump (0.5 HP)	1	375	0.5	187.5
7	Laptop Charger	2	100	3	300
8	Phone Charger	4	20	4	80
9	Electric Iron	1	1200	0.5	600
10	Microwave Oven	1	800	0.25	200
11	DSTV Decoder	1	30	8	240
12	Home Theatre	1	50	5	250
	Sub-Total				**15177.5**
	Safety Margin (20%)				**3035.5**
	Total Daily Energy Consumption				**18213 Wh (18.21 kWh)**

2.3.1 Component System Sizing:

The system components were sized to reliably meet the 18.21 kWh/day energy demand, considering Port Harcourt's 4.5 peak hours of sun (PSH) and an overall system efficiency of 75%.

2.3.2 PV component sizing

The average daily horizontal solar irradiance on surfaces in Port Harcourt is measured at 4.77 kWh/m^2/day. The irradiance of photovoltaic at STC is 1000. It has been found that the panel generation factor (PGF) of the location to which the PV system will be installed is given as

$$PGF = {}^{DSRL}/_{IPV\ at\ STC}. \quad (1)$$

where DSRL is the daily solar radiation, IPV at STC is the PV irradiance at STC

This factor varies with the variation of the site and has no unit.[12]

The total PV panel energy required is multiplied by the system losses compensation factor known to be a constant 1.33. the total energy consumption = 18.21kWh, energy loss in the system = 1.3

Thus, Total PV panel energy required = 23673Wh/day.

2.3.3 PV system modules sizing

To size the PV modules, first determined the total watt peak rating required to operate the PV.

$$P_{pv} = \frac{E_d}{PSH * \eta cr * \eta inv} \quad (2)$$

E_d is the daily energy consumption of the residence in kWh/day, η_{CR} is the charge regulator efficiency, η_{inv} is the inverter efficiency, PSH is the peak sunshine hour (h/day). For simplicity, the equation below was used

$$P_{pv} = \frac{pv\ module\ energy}{PGF} \quad (3)$$

Using manufacturers specification, the PV module peak power rated output was obtained and used to calculate system requirement for the number of modules .

$$No.\ of\ modules\ required = \frac{total\ watt\ peak}{PV\ module\ peak\ rated\ output} \quad (4)$$

The number of modules required for the design is obtained as 10. This translates to 10 monocrystalline solar panels, each rated at 550 Wp, yielding a total of 5.5 kWp. These panels are selected for their high efficiency and suitability for typical residential roof spaces.

2.3.4 PV system Battery sizing

Battery capacity required is known as Ampere-hour (Ah). The total ampere-hour can be obtained using the following formula:

$$C_{BAH} = \frac{AD * E_{db}}{DOD * \eta_{BAH} V_B} \quad (5)$$

where E_{db} is the daily energy required from the battery, AD is autonomy days, is the ampere-hour, η_{BAH} is the efficiency of the battery cell, and V_B is the selected nominal DC voltage of the battery block [13,14]. The values of the factors considered while calculating for battery size are battery loss 0.85, 1.5-days of autonomy, depths of discharge, DOD – 0.75, and battery's nominal voltage. From our battery specification, the nominal voltage is 12V.
C_{BAH}= 1148.95 Ah
The number of batteries for the PV system was found by:

$$No. of\ Batteries = \frac{required\ battery\ capacity}{capacity\ of\ 1{-}battery} \quad (6)$$

where required battery capacity was obtained to be 1148.95, capacity of 1-baterry=41
No. of batteries for the PV = 28

2.3.5 PV system Inverter sizing

To allow for safe and efficient operation the general rule of thumb is that the size of the inverter should be similar to the DC rating of solar panel system or solar generator. A 5 kVA hybrid inverter was selected as the central component, capable of handling the household's peak simultaneous load (estimated around 2.5 kW) and providing seamless transition between solar battery, and grid power

2.4 Performance Analysis Metrics:

The technical performance was assessed using energy yield (total kWh produced), overall system efficiency (considering all losses like temperature, soiling, wiring, inverter, and battery inefficiencies), and reliability/autonomy (the system's ability to consistently met demand, specifically how long batteries can power loads without solar or grid input). A comprehensive quantification of various losses was factored in to ensure realistic performance predictions [15].

2.5 Economic Analysis Metrics:

The economic viability was evaluated through several key metrics. Initial Capital Cost (CAPEX) encompasses all component and installation expenses. Operational and Maintenance (O&M) Costs include recurring expenses like battery replacements and routine servicing. Energy Savings quantify the financial benefits from reduced reliance on grid electricity and expensive generator fuel. Key financial indicators calculated include Payback Period (time to recover initial investment), Return on Investment (ROI) over the system's lifespan, and the Levelized Cost of Electricity (LCOE), which provides an average cost per kWh generated over the system's lifetime, allowing for direct comparison with conventional energy sources [16].

3.0 RESULTS AND DISCUSSION

The results of computational modeling (design and sizing) and simulation are presented in this chapter. PVsyst software was used for simulation in this study. All the figures are generated through the simulation process for proposed site only.

3.1 Results

Figure 1 presents the module orientation and tilt angle adopted for the simulation. The filed structure is a fixed tilted plane of tilt 15^0 and plane orientation azimuth at 0^0. The optimization is done for whole year with respect to optimum loss zero percent and energy collector on plane is 1740 kWh/m^2.

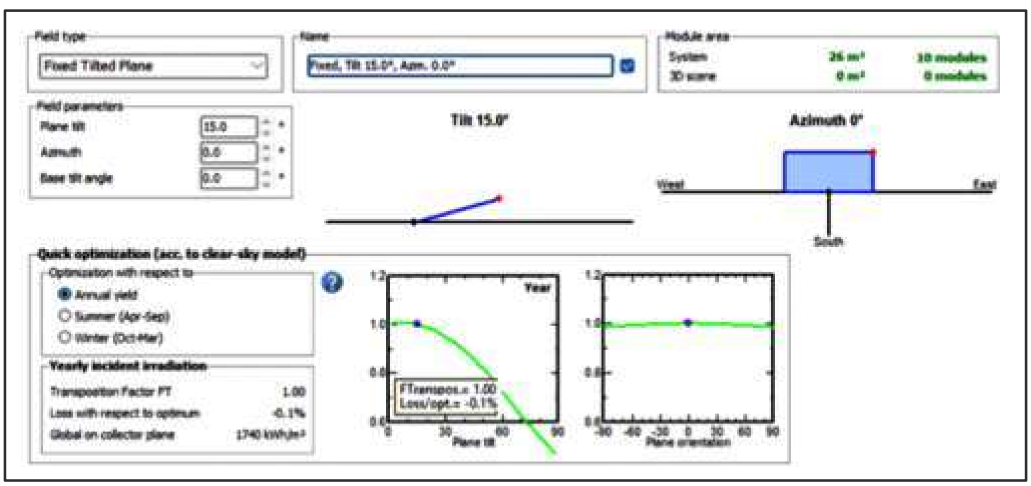


Figure 1. Module orientation and tilt angle.

Figure 2 shows the schematic diagram of a framework Layout of Hybrid system Within the on-grid PV system, the inverter module was chosen from the inverter database. All the strings of PV modules associated must be homogeneous, suggest undefined modules, the same number of modules in a course of action, the same presentation, etc.

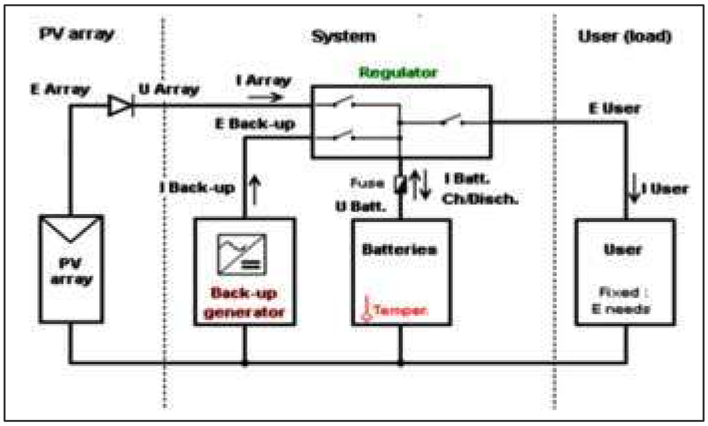
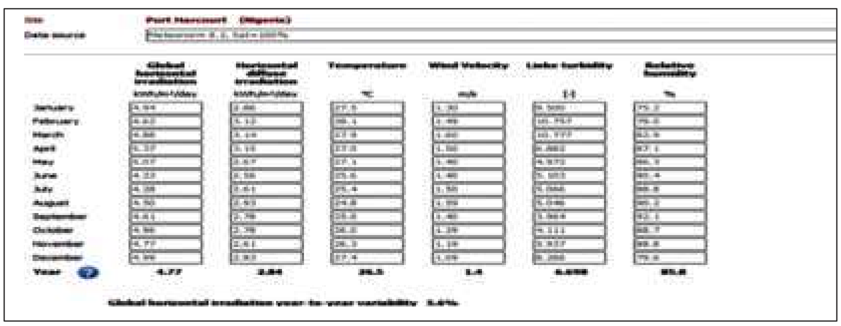


Figure 2. Schematic diagram of a Hybrid PV system layout.

3.1.1 The Monthly/Daily Solar Irradiation of the Study Area.

The solar global irradiation of the site per day for the 12-months of the year is generated through the meteonorm 8.2 data site presented in figure 3. The result shows an average daily global irradiation of 4.77 kWh/m^2/day while diffused irradiance at 2.84 kWh/m^2/day. The average temperature at 26.5^{0}C, wind velocity at 1.4m/s, and a relative humidity of 85.8%. The linked turbidity averaged at 6.698 figure 3.



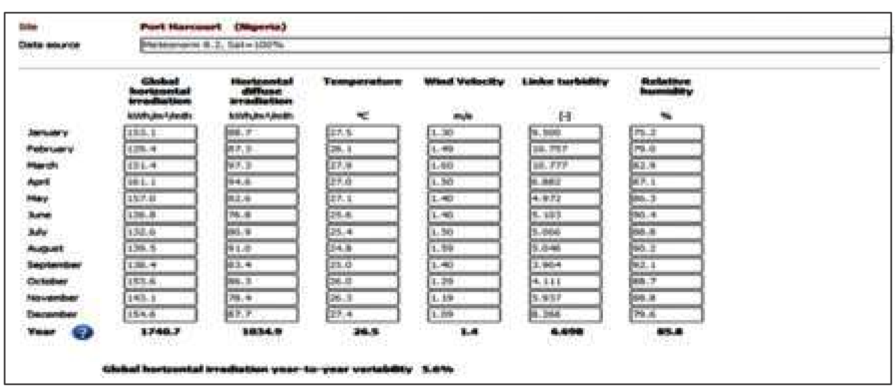
Site: Port Harcourt (Nigeria)
Data source: Meteonorm 8.2, Sat=100%

	Global horizontal irradiation	Horizontal diffuse irradiation	Temperature	Wind Velocity	Linke turbidity	Relative humidity
	kWh/m²/day	kWh/m²/day	°C	m/s	[-]	%
January	4.94	2.86	27.5	1.30	9.500	75.2
February	4.62	3.12	28.1	1.49	10.757	79.0
March	4.88	3.14	27.9	1.60	10.777	82.9
April	5.37	3.16	27.0	1.50	6.882	87.1
May	5.07	2.67	27.1	1.40	4.972	86.3
June	4.22	2.56	25.6	1.40	5.103	90.4
July	4.28	2.61	25.4	1.50	5.066	88.8
August	4.50	2.93	24.8	1.59	5.046	90.2
September	4.61	2.78	25.0	1.40	3.904	92.1
October	4.96	2.78	26.0	1.29	4.111	88.7
November	4.77	2.61	26.3	1.19	5.937	88.8
December	4.99	2.83	27.4	1.09	8.266	79.6
Year	4.77	2.84	26.5	1.4	6.698	85.8

Global horizontal irradiation year-to-year variability 5.6%

Figure 3. Daily Global Irradiance per day for the 12 months of the year

Figure 4 depicted the site global irradiation per month for the 12-months of the year generated from the meteonorm 8.2 sat-100% data site. The average global irradiation obtained per month as 1740.7 kWh/m^2/m while diffused irradiance is at 1034.9 kWh/m^2/m, average temperature, and wind velocity correlative to global irradiation per day at 26.5^{0}C, 1.4 m/s. The relative humidity and link turbidity 6.698 and 85.8 % respectively.



Site: Port Harcourt (Nigeria)
Data source: Meteonorm 8.2, Sat=100%

	Global horizontal irradiation	Horizontal diffuse irradiation	Temperature	Wind Velocity	Linke turbidity	Relative humidity
	kWh/m²/mth	kWh/m²/mth	°C	m/s	[-]	%
January	153.1	88.7	27.5	1.30	9.500	75.2
February	129.4	87.3	28.1	1.49	10.757	79.0
March	151.4	97.3	27.9	1.60	10.777	82.9
April	161.1	94.6	27.0	1.50	6.882	87.1
May	157.0	82.6	27.1	1.40	4.972	86.3
June	126.8	76.8	25.6	1.40	5.103	90.4
July	132.6	80.9	25.4	1.50	5.066	88.8
August	139.5	91.0	24.8	1.59	5.046	90.2
September	138.4	83.4	25.0	1.40	3.904	92.1
October	153.6	86.3	26.0	1.29	4.111	88.7
November	143.1	78.4	26.3	1.19	5.937	88.8
December	154.6	87.7	27.4	1.09	8.266	79.6
Year	1740.7	1034.9	26.5	1.4	6.698	85.8

Global horizontal irradiation year-to-year variability 5.6%

Figure 4. Global Irradiation per Month for the 12-months of the Year.

Figure 5 explains how the load in the House is distributed during use. The energy bulbs are switched on between the hours of 12am-3pm, the ceiling fans are in use between 5pm-9pm, desktop computers, fridges, and mobile chargers are also distributed in certain hourly proportions. The same distribution also applies to fractions of the values of daily energy extracted from the annual value of a 24-hr timeline. The results were generated by the software after load values have been inputted into it and the simulation is done. The days of autonomy fixed for the system are 1.5 days.

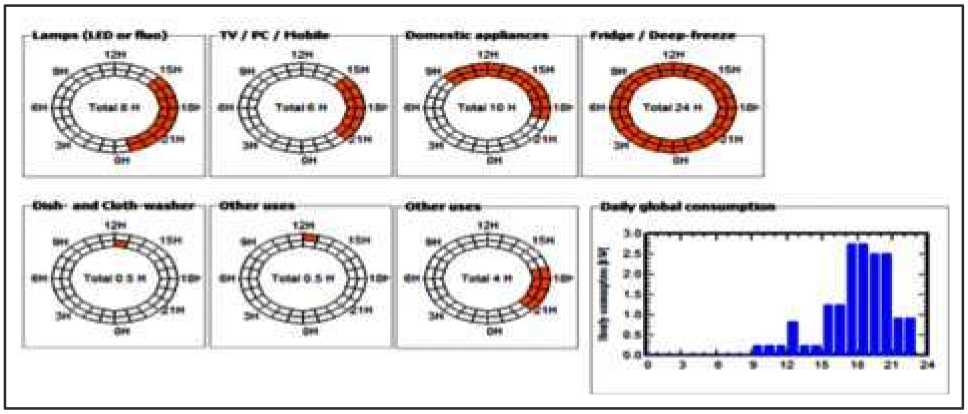


Figure 5. Load Distribution During Use.

The Performance ratio (PR) is the ratio of the final PV system yield (Yf) and the reference yield (Yr) [27].

$$PR = \frac{Y_f}{Y_r} \quad (7)$$

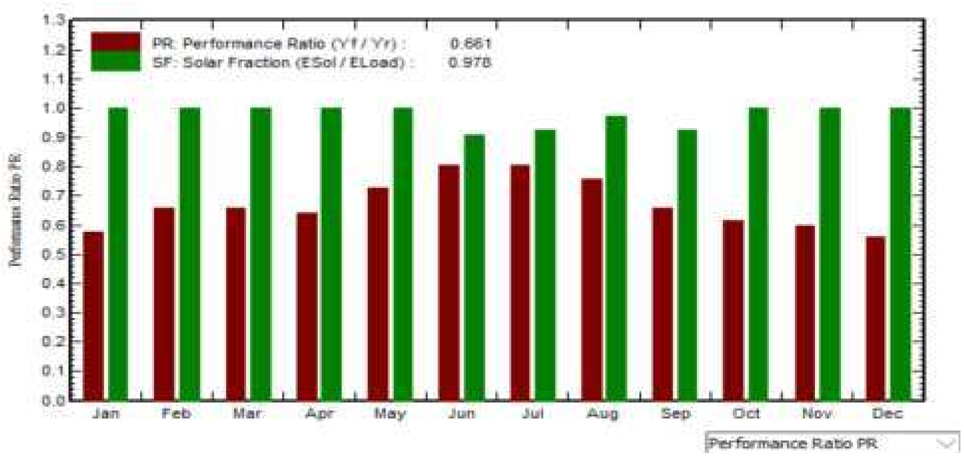


Figure 6. Performance Ratio and Solar Fraction

The highest PR recorded in the month of December is 86% due to low module temperature and lowest PR 64% is obtained in the month of April due to the high temperature of the PV module. Whereas the annual average PR is 72.8%. The month-to-month vitality generation with the losses has appeared in Fig. 5. There are distinctive sorts of field losses that happen within the photovoltaic frameworks all through the year which is depicted in Fig. 6

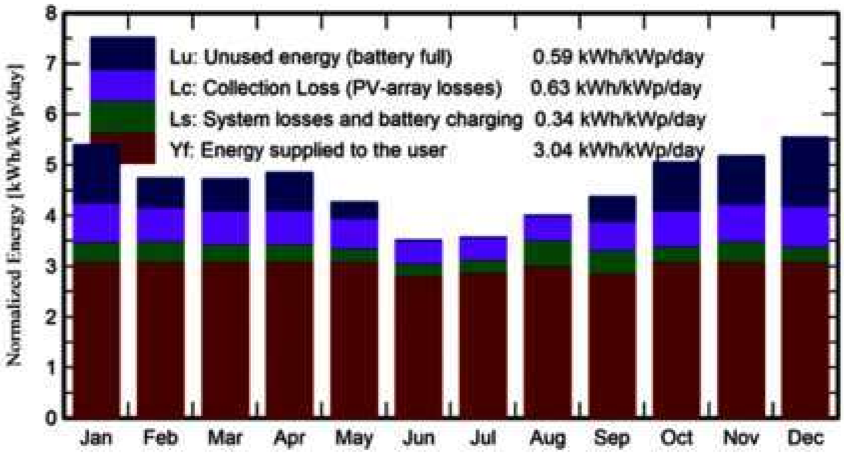


Figure 6. Monthly Normalized productions with losses.

Figure 6 shows the normalized production (kWh/kWp/day) of energy against the months of the year. This gives a response of Collection loss Lc with value 0.63 kWh/kWp/day, System losses (inverter.) and battery charging Ls with value 0.34 kWh/kWp/day and the produced energy (inverter output) Yf with a value 3.04 kWh/kWp/day value. The unused energy Lu (battery full) 0.59kWh/kWp/day.

	GlobHor	GlobEff	E_Avail	EUnused	E_Miss	E_User	E_Load	SolFrac
	kWh/m²	kWh/m²	kWh	kWh	kWh	kWh	kWh	ratio
January	153.1	164.1	761.7	192.5	0.00	529.5	529.5	1.000
February	129.4	130.0	601.8	86.5	0.00	478.3	478.3	1.000
March	151.4	143.2	665.9	104.3	0.00	529.5	529.5	1.000
April	161.1	141.6	666.1	120.8	0.00	512.4	512.4	1.000
May	157.0	128.0	601.7	53.7	0.00	529.5	529.5	1.000
June	126.8	101.5	481.7	0.0	46.21	466.2	512.4	0.910
July	132.6	106.9	509.0	0.0	37.98	491.5	529.5	0.928
August	139.5	120.2	574.9	0.0	13.79	515.7	529.5	0.974
September	138.4	127.7	603.7	78.2	37.73	474.7	512.4	0.926
October	153.6	153.1	716.8	160.7	0.00	529.5	529.5	1.000
November	143.1	152.3	708.2	154.7	0.00	512.4	512.4	1.000
December	154.6	168.6	783.9	227.9	0.00	529.5	529.5	1.000
Year	1740.7	1637.2	7675.5	1179.2	135.71	6099.0	6234.7	0.978

Figure 7 depicts the yearly equalizations and fundamental outcomes of the on-grid PV framework. The vitality can be conveyed to the client is 6099.0 kWh. The execution proportion within the simulation program was almost comparative for each month as shown in Fig 6.

It is evident that the average annual energy requirement for the Household is 18.56 kWh (6774.4 kWh/day) and the energy available through solar panel is 7675.5 kWh, where the energy supplied to the user is 6099.0 kWh (16.71 kWh/day) a slightly less than the required load. The reduced power capacity of the system is because of various kinds of losses.

3.1.2 Energy Load Assessment Results:

The detailed load assessment for a typical residential house in Port Harcourt revealed a total daily energy consumption of 18.21 kWh, including a 20% safety margin. As presented in Table 2, the air conditioner (32.94%) and refrigerator (19.77%) were identified as primary energy consumers, underscoring the significant impact of cooling and continuous refrigeration needs in the local climate. This comprehensive understanding of the load profile was crucial for accurately sizing the solar PV system.

Table 2: Calculated Daily Energy Consumption for a Typical Residential House in Port Harcourt

S/N	Appliance	Quantity	Power Rating (W)	Daily Usage (Hours)	Daily Energy Consumption (Wh)	Percentage of Total Load (%)
1	LED Bulbs (9W)	10	90	8	720	3.95
2	Ceiling Fans	4	240	10	2400	13.18
3	Television (LED)	1	100	6	600	3.29
4	Refrigerator (Medium)	1	150	24	3600	19.77
5	Air Conditioner (1.5 HP)	1	1500	4	6000	32.94
6	Water Pump (0.5 HP)	1	375	0.5	187.5	1.03
7	Laptop Charger	2	100	3	300	1.65
8	Phone Charger	4	20	4	80	0.44
9	Electric Iron	1	1200	0.5	600	3.29
10	Microwave Oven	1	800	0.25	200	1.1
11	DSTV Decoder	1	30	8	240	1.32
12	Home Theatre	1	50	5	250	1.37
	Sub-Total				**15177.5**	**83.33**
	Safety Margin (20%)				**3035.5**	**16.67**
	Total Daily Energy Consumption				**18213 Wh (18.21 kWh)**	**100**

3.1.2 Designed System Specifications:

The designed 5 kVA hybrid solar PV system incorporates 10 monocrystalline 550 Wp solar panels (5.5 kWp total), a 5 kVA hybrid inverter, a 48V battery bank (28 x 200 Ah deep-cycle gel batteries) providing 1.5 days of autonomy, and a 150A, 48V MPPT charge controller. This configuration, detailed in Table 3, ensures sufficient energy generation and storage to meet the identified daily load. The hybrid inverter is critical for seamlessly managing power flow from solar, batteries, and the grid, crucial for Port Harcourt's unreliable power supply.

Table 3: Designed 5 kVA Hybrid Solar PV System Specifications

Component	Specification	Quantity	Notes
Solar PV Panels	Monocrystalline, 550 Wp	10	High-efficiency, good for limited roof space. Total 5.5 kWp.
PV Array Configuration	2 strings of 5 panels in series		Optimizes voltage for MPPT charge controller/inverter.
Hybrid Inverter	5 kVA / 4000 W (Rated Power), 48V DC Input	1	Pure Sine Wave, MPPT functionality, Grid-Interactive, Automatic Transfer Switch.
Battery Bank (Type)	Deep Cycle Gel Batteries, 12V	28	Robust, low maintenance, suitable for frequent cycling.
Battery Bank (Capacity)	200 Ah (each battery)		Configured as 7 parallel strings of 4 batteries in series (48V nominal). Total 1344 Ah at 48V usable.
Battery Autonomy	1.5 Days (at 50% DoD)		Provides sufficient backup during extended grid outages and low solar periods.
Charge Controller	MPPT, 150A, 48V	1	Maximizes power harvest from PV array, efficient charging.
Mounting Structure	Aluminum/Galvanized Steel Rooftop Mount	1 set	Durable, corrosion-resistant, designed for local wind loads.
Cabling	DC and AC rated, UV resistant, appropriate gauge	~100m+	Minimizes voltage drop and ensures safety.
Protection Devices	DC/AC Breakers, Fuses, Surge Protectors, Grounding	1 set	Essential for system safety and component protection.

3.1.3 Technical Performance Analysis Results:

The technical analysis projects a net usable daily energy yield of 18.56 kWh from the 5.5 kWp solar array, effectively meeting the 18.21 kWh daily energy demand (Table 4). This calculation accounts for an overall system efficiency of 75%, factoring in various losses such as temperature derating (10%), soiling (3%), wiring (2%), inverter efficiency (5%), and battery inefficiencies (15% roundtrip) (Table 5). The designed system's reliability is high, with the battery bank providing approximately 1.84 days of autonomy, ensuring continuous power supply even during extended grid outages. This capability is critical for enhancing energy security in Port Harcourt.

Table 4: Estimated Energy Yield for the 5 kVA Hybrid Solar PV System

[redacted]	
Gross Daily PV Generation	24.75 kWh
Net Usable Daily Energy Yield	18.56 kWh
Net Usable Monthly Energy Yield	556.8 kWh (18.56 kWh/day * 30 days)
Net Usable Annual Energy Yield	6774.4 kWh (18.56 kWh/day * 365 days)

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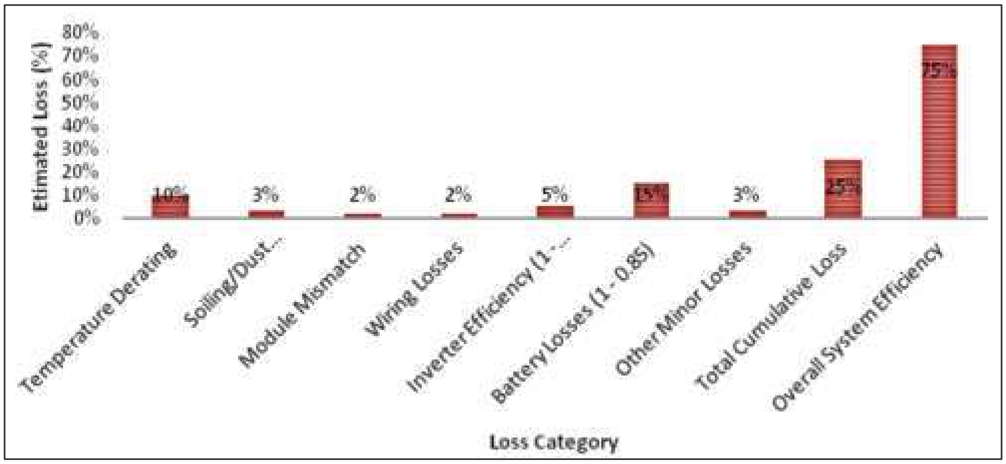

Figure 7. Estimated System Losses and Overall Efficiency [15, 17].

3.1.4 Economic Viability Analysis Results:

The initial capital cost (CAPEX) for the 5 kVA hybrid system is estimated at ₦12,450,000, with the battery bank accounting for the largest share (66.67%) due to the reliance on deep-cycle gel batteries (Table 6). This high upfront cost represents the primary financial barrier.

Table 5: Estimated Initial Capital Cost (CAPEX) for 5 kVA Hybrid Solar PV System

[redacted]					
1	Solar Panels (550 Wp Monocrystalline)	₦300,000	10	₦3,000,000	28.57
2	Hybrid Inverter (5 kVA)	₦1,200,000	1	₦1,200,000	11.43
3	Deep Cycle Gel Batteries (200 Ah, 12V)	₦250,000	28	₦7,000,000	66.67
4	MPPT Charge Controller (150A, 48V)	₦350,000	1	₦350,000	3.33
5	Mounting Structures (Aluminum)	₦200,000	1 set	₦200,000	1.9
6	Cabling & Electrical Accessories	₦150,000	1 set	₦150,000	1.43
7	Protection Devices (Breakers, SPDs, Fuses)	₦100,000	1 set	₦100,000	0.95
8	Installation Labor	₦400,000	1	₦400,000	3.81
9	Transportation & Logistics	₦50,000	1	₦50,000	0.48
Total Estimated Initial Capital Cost (CAPEX)				**₦12,450,000**	**100**

Operational and Maintenance (O&M) costs are significantly influenced by battery replacements, with an average annual O&M cost of ₦1,804,500 (including an annualized battery replacement cost of ₦1,750,000 over 4 years). The annual energy savings from displacing generator use (estimated at ₦1,380,000 annually) present a strong incentive, as generator power (approx. ₦162.5/kWh fuel-only, higher with maintenance) is far more expensive than grid power (₦60/kWh) [6].

The simple payback period is challenging to present positively when accounting for frequent lead-acid battery replacements, indicating that pure cash-on-cash return can be stretched. However, the Levelized Cost of Electricity (LCOE), calculated at approximately ₦205.5/kWh (when considering longer-lasting lithium-ion batteries and total lifetime costs), is higher than grid power but competitive with or lower than the total cost of relying on a generator over the system's 25-year lifespan. This suggests that the economic value proposition extends beyond simple kWh cost to encompass the value of reliable, uninterrupted power, which is a premium in Port Harcourt. The Return on Investment (ROI), while potentially marginally negative on a purely financial basis with lead-acid batteries, becomes significantly more attractive when factoring in the avoided costs of generator ownership, maintenance, and the intangible benefits of energy independence and improved quality of life.

3.2 Discussion

The gross daily PV generation was obtained to be 24,75kWh and the net usable daily energy yield is 18.56 kWh, the net usable monthly energy yield 556.8kWh, and the net usable energy yield annually is 6774.4 kWh this is slightly greater than the required daily energy consumption of 18.21kWh and the net required annual energy consumption of 6646.65 kWh. The technical performance analysis confirms that the 5 kVA hybrid solar PV system is entirely feasible for meeting the energy demands of a typical Port Harcourt residence. The system's ability to seamlessly switch between solar, battery, and grid sources directly addresses the pervasive issue of unreliable grid power, significantly enhancing energy security and improving quality of life for residents. This aligns with the results on the technical viability of solar PV systems in similar climates presented by [18, 19].

However, the economic viability is largely dependent on the high initial capital investment, primarily driven by the cost of energy storage. While the system effectively displaces expensive generator fuel, the long-term O&M costs, particularly for lead-acid battery replacements, challenge a straightforward positive financial return when viewed solely through traditional payback metrics. This contrasts with studies from regions with strong net metering or lower component costs [20]. The absence of robust net metering policies in Nigeria further limits potential revenue streams [21]. Nevertheless, the true economic value in Port Harcourt lies in the avoidance of constant generator costs and the immense value of guaranteed, uninterrupted power, which significantly outweighs the intermittent and poor quality of grid supply. The system offers energy independence, reduced carbon footprint, and enhanced property value, albeit with the need for substantial upfront financing and consideration of longer-lasting battery technologies like lithium-ion to improve lifetime economics. The current market context, particularly the high cost of fuel post-subsidy removal, makes solar PV increasingly competitive as a reliable alternative.

4.0 CONCLUSION

This study concludes that the design of a 5 kVA hybrid solar photovoltaic system is technically feasible and highly beneficial for residential applications in Port Harcourt, Nigeria. The system effectively meets the average daily energy demand of 18.21 kWh, providing a robust and reliable power supply that directly addresses the chronic issues of grid unreliability and power outages. While the initial capital investment is substantial, particularly for battery storage, the system offers significant long-term economic advantages by displacing costly generator fuel consumption and maintenance. When considering the Levelized Cost of Electricity and the invaluable benefit of consistent, uninterrupted power, solar PV stands as a viable and superior alternative to the prevailing energy landscape in the region, fostering true energy independence and environmental sustainability for households in Port Harcourt.

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APPENDIX 1.

Code snippet graph TD

A [Solar PV Array (5.5 kWp)] > B (DC Combiner Box/Fuse) B > C (MPPT Charge Controller-150A, 48V) C > D (Battery Bank - 48V, 1340Ah usable) D - DC Power --> E(Hybrid Inverter-5 kVA, 48V) A -DC Power > E-E-AC Power > F(AC Distribution Board) F -AC Power > G[Residential Loads] F-AC Power > H[Utility Grid] H-AC Power (Input/Output) > E

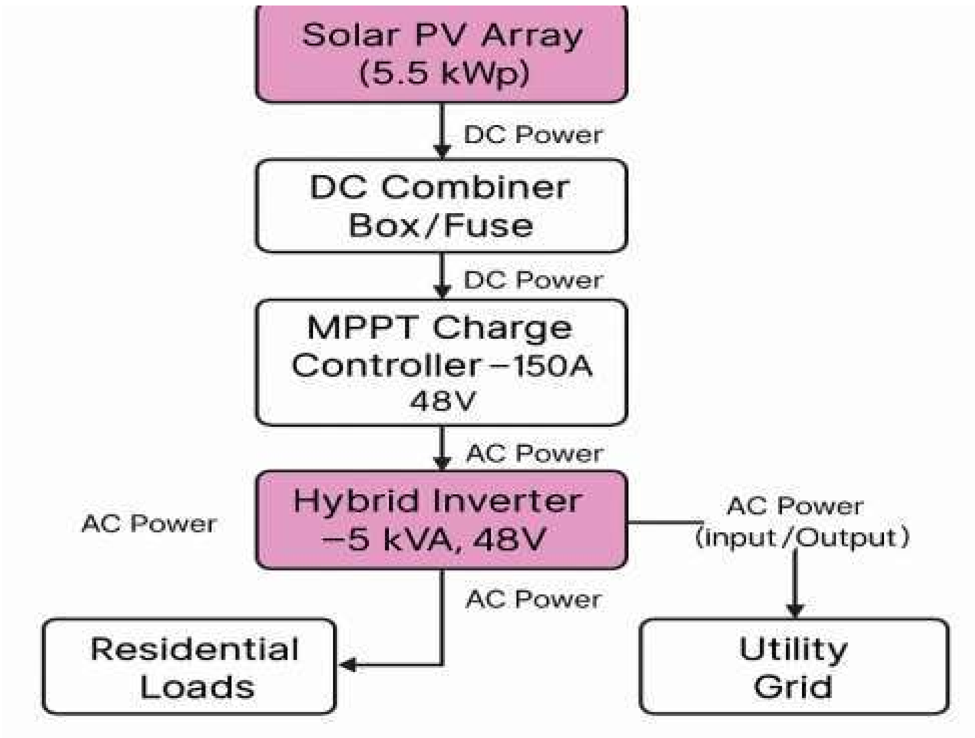

Figure 1: Block Diagram of a 5 kVA Hybrid Solar PV System for Residential Use. ***Source: (Renewable Energy Handbook, 2019).***