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Simulation and Analysis of a Standalone PV Solar Power Plant for a Housing Estate in Abuja, Nigeria

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Abstract- Abuja is located within the guinea savannah climatic zone of Nigeria and receives a global horizontal irradiation (GHI) of about 2.04 MWh/m^2/year. With this, solar photovoltaic (PV) systems can serve as the main source of electricity for homes and businesses in the city. To further expose this reality, a feasibility study was carried out. A standalone PV solar power plant for a typical 200 bungalow housing estate in Abuja, Nigeria was designed and simulated to study its technical and economic feasibility using PVsyst 7.3 software. The design shows that with the 2.04 MWh/m^2/year global horizontal irradiation reaching Abuja, a 360 kWp PV system is needed to supply the energy needs of an estate with an energy demand of 1,480 kWh/day. The system will produce a total of 571,288 kWh of electric energy per year with a performance ratio of 75.4 % and a solar fraction of 96.7%. The proposed project is highly feasible as the economic evaluation results show that the system's installation cost is 399,350 USD at a specific cost of 1.11 USD/kWp, and the net present value (NPV) is positive at 932,230.45 USD, 854,946.51 USD, and 808.576.15 USD, respectively for the three cases of 0%, 50%, and 80% loan financing. Housing Estate and Solar Energy developers are therefore called upon to take advantage of the positive outcome of this study to promote Solar PV systems deployment in Abuja, Nigeria.

Keywords: Abuja, solar PV system, power plant, housing estate, technical simulation, economic evaluation

1. Introduction

Abuja, the Federal Capital Territory (FCT) of Nigeria, is located at latitude and longitude coordinates 9.0579 N/7.4951 E. The city falls within the guinea savannah climatic zone of Nigeria [1] with a Global Horizontal Irradiation (GHI) of 2,035 kWh/m^2/year. This GHI value positions the city as an area where solar PV systems will be highly feasible. This is because studies have shown that solar PV systems are feasible even in areas with lower GHI values like Enugu and Ebonyi [2,3] which lie within the tropical rainforest climatic zone of Nigeria [1]. Fig.1 shows a map of Nigeria with Abuja located within the guinea savannah climatic zone.

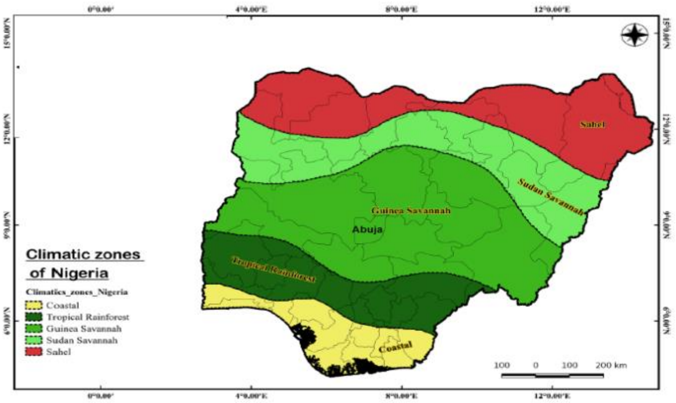


Fig.1. Map of Nigeria with Abuja located within the guinea savannah climatic zone [1]

Despite the huge solar energy resources available in Abuja, it is sad to note that numerous housing estates in Abuja, except a few recent ones [4-6] , were planned and developed without considering incorporating solar power plants to provide the energy needs of the estates. This is worrisome considering the fact that the grid electric supply in Abuja and other parts of Nigeria has remained erratic for years despite the huge investments in the sector [7,8]. This erratic grid power supply has hampered development and the standard of living in the city as homes and businesses are made to rely on generators for their electric energy needs. This has greatly increased the cost of living and production in the city as the cost of running electric power generators in Abuja and Nigeria in general is quite high [9].

One of the reasons for low levels of solar energy resource utilization for electricity generation in Abuja is a lack of awareness of the capabilities and benefits of PV systems [10]. Another reason is technical issues like the early failure of existing PV systems' components in Nigeria due to poor design and lack of maintenance, and their dispiriting effect on potential new users. This can be attributed to inadequate human capacity building and associated training in solar energy development, installation, and maintenance in the country [11]. Other reasons include poverty which has limited the capacity of the majority of the masses to afford the high initial cost of PV system installation, and the fear of theft and vandalism due to the high level of insecurity in the country [11]. Establishing industries in Nigeria for local production of PV panels and system components will help drive down the installation costs. An increase in capacity development training, research, and publications in the area of solar PV systems will go a long way in tackling some of the issues [12].

A standalone solar PV power plant with battery storage comprises a PV array that consists of PV modules connected in series and parallel to realize the needed peak power. Other components of the system which are collectively called the balance of system (BOS) components include a charge controller, battery bank, and inverter. The charge controller regulates the flow of current from the PV modules to the battery bank and inverter while the inverter converts the DC voltage from the PV modules and battery to an AC voltage that is delivered to the load. The battery bank works to store the excess energy from the PV modules when solar radiation is sufficiently available and supplies the stored energy via the inverter to power the loads when solar radiation is low or unavailable. The block diagram of a standalone solar PV power plant with battery storage is shown in Fig.2.

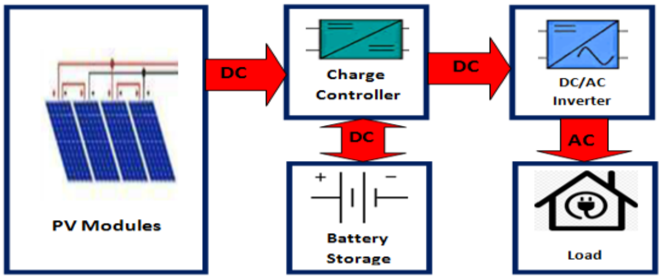


Fig. 2. Block diagram of a standalone solar PV power plant with battery storage

To design a PV power plant, some pre-design parameters are needed. They include the daily sun hour of the location which is the average daily solar irradiation divided by the solar irradiance reaching the earth under standard test conditions (that is 1,000 W/m^2), the DC input voltage of the system, the days of autonomy which is the number of days the battery can supply the needed power in the absence of solar radiation, the wattage of the load devices and how many hours each will be ON daily, and the PV module's parameters. With this information, the PV system can be manually designed using a set of design equations. These equations as obtained from literature [13] are as follows: The daily average energy demand (Ed) is calculated from Equation 1,

$$E_d = \sum_{i=1}^{n} P_{Li} t_i \tag{1}$$

where P_{Li} is the wattage of the ith load device and t_i is the time in hours the ith device will be ON in a day. The battery bank sizing and cost estimation can then be done using Equations 2 to 8.

$Estimated\ Energy\ Storage,$

$$E_{est} = E_d \times D_{aut} \tag{2}$$

$Safe\ Energy\ Storage,$

$$E_{safe} = \frac{E_{est}}{D_{disch}} \tag{3}$$

$Total\ Capacity\ of\ Battery\ Bank,$

$$C_{tb} = \frac{E_{safe}}{V_b} \tag{4}$$

$Total\ Number\ of\ Batteries\ in\ the\ Bank,$

$$N_{tb} = \frac{C_{tb}}{C_b} \tag{5}$$

$Number\ of\ Batteries\ in\ Series,$

$$N_{sb} = \frac{V_{dc}}{V_b} \tag{6}$$

$Number\ of\ Batteries\ in\ Parallel,$

$$N_{pb} = \frac{N_{tb}}{N_{sb}} \tag{7}$$

$Cost\ of\ Battery\ Bank,$

$$B_{bcost} = N_{tb} \times B_{cost} \tag{8}$$

where D_{aut} = days of autonomy, D_{disch} = maximum depth of discharge of batteries, V_b = battery voltage, V_{dc} = DC input voltage, and B_{cost} = cost of one battery. The PV array sizing and cost estimation are done using equations 9 to 16.

Required Daily Energy Demand,

$$E_{rd} = \frac{E_d}{\eta_b \eta_i \eta_c} \tag{9}$$

Average Peak Power,

$$\bar{P}_{peak} = \frac{E_{rd}}{T_{sh}} \tag{10}$$

Total dc Current,

$$I_{dc} = \frac{\bar{P}_{peak}}{V_{dc}} \tag{11}$$

Temperature Compensated Module Rated Power,

$$P_{mt} = 0.8 \times P_m \tag{12}$$

Total Number of Modules,

$$N_{tm} = \frac{\bar{P}_{peak}}{P_{mt}} \tag{13}$$

Number of Modules in Series,

$$N_{sm} = \frac{N_{sb} \times V_{bc}}{V_{rm}} \tag{14}$$

Number of Modules in Parallel,

$$N_{pm} = \frac{N_{tm}}{N_{sm}} \tag{15}$$

Total Cost of PV Array,

$$A_{cost} = N_{tm} \times M_{cost} \tag{16}$$

where η_b = efficiency of the battery, η_i = efficiency of the inverter, η_c = efficiency of charge controller, T_{sh} = average daily sun hour, P_m = module-rated power, V_{bc} = charging voltage for each battery, V_{rm} = PV module rated voltage, and M_{cost} = cost of one PV module. The charge controller and inverter sizing are done using equations 17 to 19.

Required Charge Controller Current,

$$I_{rcc} = I_{sc} \times N_{pm} \times F_{safe} \tag{17}$$

Number of Charge Controllers,

$$N_{cc} = \frac{I_{rcc}}{I_{cc}} \tag{18}$$

Total Cost of Charge Controllers,

$$C_{tcost} = N_{cc} \times C_{cost} \tag{19}$$

Total Inverter Power,

$$P_{ti} = F_{safe}(P_{nc} \times 3P_c) \tag{20}$$

Number of Inverters,

$$N_i = \frac{P_{ti}}{P_i} \tag{21}$$

Total Cost of Inverters,

$$INV_{tcost} = N_i \times INV_{cost} \tag{22}$$

where I_{sc} = PV module's short circuit current, F_{safe} = Safety Factor = 1.25, I_{cc} = charge controller rated current, C_{cost} = cost of one charge controller, P_{nc} = power of non-inductive loads, P_c = power of inductive loads, P_i = inverter-rated power, and INV_{cost} = cost of one inverter.

PV systems can also be designed using design and simulation softwares. Some of the softwares that can be used in the design and/or simulation of solar PV systems include PVsyst, RETScreen, PV F-Chart, INSEL, TRNSYS, Solar Advisor Model (SAM), SolarDesign Tool, SolarPro, HOMER, and PV-DesignPro-G [14]. PV simulation softwares on the market have different merits and limitations based on the particular areas of interest of the developers [15]. The four most popular of these softwares due to their features are HOMER, RETScreen, SolarPro, and PVSyst.

Before a solar PV power plant can be installed in an area, it is pertinent to do a techno-economic feasibility study to ascertain among other things, the initial financial implications, running cost, and energy payback period. Such a feasibility study is not only beneficial to the PV system developers but also the governments, housing estate developers, and the general public, as it is a way of creating awareness and drawing attention to the benefits of adopting solar PV systems for powering homes and businesses. Such awareness creation and developments that follow it contribute to the actualization of the United Nations' envision 2030 goals 7 and 11 [16,17].

Several studies have been done on the development of more efficient components of a PV system and also to ascertain the feasibility of different PV systems at different locations in the world. In the area of PV system components development, many researchers have successfully worked to develop more efficient maximum power point tracking (MPPT) controllers to enable the use of PV systems in powering high energy demanding devices like arc welding machines, industrial DC motors, and heaters [18-23]. Other successful PV system development works done by researchers include the design and performance analysis of a Solar Powered Dough Maker [24], the development of a Floating Solar Photovoltaic (FSPV) system for powering sustainable energy-based mini micro-grid [25], and the development of 2nd-Generation solar charging system in the USA [26]. In Nigeria, studies have been done on: the feasibility of deploying a PV-diesel hybrid power plant for a Base Transmitter Station located in Enugu [2]; the deployment of a PV/BIOMASS hybrid system for a rural community in Ebonyi state [3]; the effectiveness of replacing the 650 VA generator used by small homes and businesses in Nigeria with a

650 Wp PV system [27]; the feasibility of powering some Data Centers in Abuja and Enugu State with hybrid solar PV/Grid power system [28]; benefits of introducing grid-connected PV system in Nigeria [29]; the potential of a solar-wind hybrid electricity generating system to supply and meet the electric energy needs of a rural community in Rivers State, Nigeria [30]; and the feasibly of deploying PV-Diesel-Battery hybrid power plants in Nigeria [9]. These studies have revealed that PV systems are feasible at several locations in Nigeria. Feasibility studies of solar PV systems have also been done in other countries like India [31-33], Jordan [34], Pakistan [35,36,37], Algeria [38,39], Sudan [40], Indonesia [41,42], Thailand [43], Vietnam [44], Turkey [45], USA [46], Croatia [47], Estonian [48], Saudi Arabia [49], and Iraq [50]. The results of these studies show that PV system is feasible at numerous locations around the world.

The feasibility study presented in this work is part of the efforts to further expose how feasible it is to install a standalone solar PV power plant to supply the electric power needs of homes in the housing estates located in different climatic zones of Nigeria. This will help draw attention to PV systems and therefore, help contribute to the realization of SDGs 7 and 11.

2. Materials and Methods

The design and techno-economic simulation were done with the help of PVsyst 7.3 software. This software was chosen because of its large metrological database sourced from NASA and many other stations across the world. Another reason for its selection was the fact that it has a large components database which facilitates the design, economic evaluation, and payback period determination. The steps involved include the site name and data selection, panels tilt and azimuth angles selection and optimization, energy demand estimation and hourly distribution, PV system pre-sizing and design, technical simulation, and economic evaluation.

2.1 Site Location and Data Selection

The geographical location of the estate, which is Abuja, was selected from the site database of the PVsyst software. The meteorological data of the location was imported from the NASA-SSE database. A table of the meteorological data showing the monthly horizontal global irradiation, horizontal diffuse irradiation, clearness index, and ambient temperature was generated and saved as shown in Table 1. The site information and imported data were also saved.

2.2 Plane Orientation and Optimization

The PV array of the system is to be mounted on a fixed tilted plane. Since the positioning of this fixed plane with respect to the Sun path varies at different periods of the year due to the earth's revolution round the Sun in an elliptical orbit, it is pertinent to optimize the fixed-plane orientation to harness the maximum possible solar irradiation in a year. Using the orientation optimization feature of the software, the field type was selected as a fixed tilted plane. With the radiation yield optimization months set at the April to September range, the azimuth was fixed at zero while the plane tilt was varied from 0 to 45^0 at intervals of 5^0. The transposition factor (which is the ratio of the global irradiation on the tilted collector plane to the global horizontal irradiation), loss with respect to optimum, and global irradiation on the collector plane were recorded. The test was repeated with the azimuth fixed at 180^0 and the results were also recorded. From the optimization test, the best plane tilt and azimuth were chosen and saved as 15^0 and 180^0, respectively.

Table 1. Monthly Meteo Data of Abuja, Nigeria from NASA-SSE Data Base

	Global Horizontal Irradiation (kWh/m²/mth)	**Horizontal Diffuse Irradiation (kWh/m²/mth)**	**Clearness Index, KT**	**Temperature (⁰C)**
January	169.90	53.10	0.630	25.9
February	163.50	53.50	0.617	26.3
March	180.10	67.70	0.569	26.7
April	171.00	67.30	0.539	26.9
May	167.10	79.10	0.510	26.5
June	165.00	67.70	0.526	24.8
July	170.20	74.60	0.524	23.6
August	172.10	71.80	0.528	23.4
September	175.50	68.20	0.568	24.1
October	174.80	67.30	0.583	25.0
November	162.00	49.00	0.609	25.6
December	164.30	51.50	0.631	25.8
Year	**2035.50**	**771.00**	**0.566**	**25.4**

2.3 Energy Demand Estimation

The energy demand of the 200 households in the estate was estimated from the wattage of the appliances in each of the households and the daily usage of the appliances. The number of each appliance in a household was multiplied by 200 to obtain the total number of the particular appliance in the estate. The number of hours each appliance is to be ON in a day and the hourly distribution of the ON-time was also keyed into the software. The hourly distribution and the daily global consumption charts are shown in Figures 3 and 4, respectively. The energy demand estimation summary is shown in Table 2.

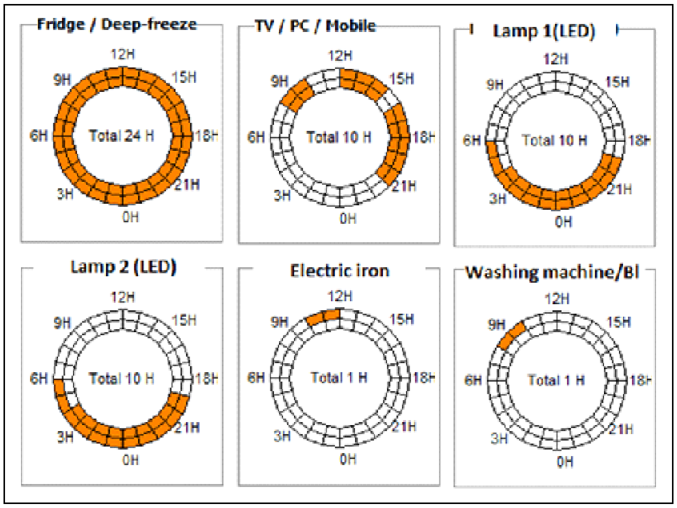


Fig. 3. The hourly distribution of energy demand

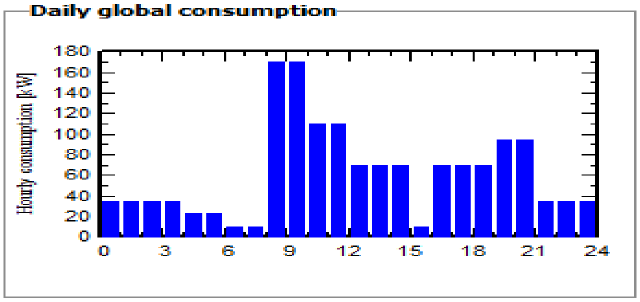


Fig. 4. Daily global consumption

2.4 PV system pre-sizing and design

The pre-sizing parameters which include the dc voltage of the system (chosen as 48 V), the number of days of autonomy (chosen as 2 days), and the loss of load probability (chosen as 10%) were keyed into the software. The needed battery which is a 12 V/220 Ah lead-acid tubular battery was selected from the battery database of the software. With the inputted pre-design parameters and battery type, the software generated the required number of batteries in series and parallel as 4 and 300, respectively.

The needed PV module type (450 Wp/35 V mono silicon PV module) was selected from the PV module database. The software then generated the possible number of modules in series to be between 2 and 4, and the possible number of modules in parallel to be between 170 and 254. With this information coupled with design acumen, the number of modules in series and parallel was chosen as 4 and 200, respectively.

Table 2. Daily energy demand of the households

S/N	Appliances	Wattage/App.	No. of App. /Household	Total wattage/App. /Household	Daily use (hour/day)	Daily energy demand per device per household	Daily energy demand per device for 200 household
1	Fridge/ Freezer	1,200 Wh/d	01	1,200 Wh/d	24	1,200 Wh/d	240 kWh/d
2	TV/PC	100 W	05	500 W	06	3,000 Wh/d	600 kWh/d
3	Lamp1(LED)	10 W	10	100 W	10	1,000 Wh/d	200 kWh/d
4	Lamp2(LED)	5 W	04	20 W	10	200 Wh/d	40 kWh/d
5	Electric Iron	1,000 W	01	1,000 Wh	01	1,000 Wh/d	200 kWh/d
6	Washing machine/ Blender	1,000 W	01	1,000 Wh	01	1,000 Wh/d	200 kWh/d
						Total	1,480 kWh/d

The needed charge controller type was selected from the charge controller database as 5,800 W/48 V/100 A MPPT charge controller. The software then generated the required number of charge controllers for the system as 50. With this, the design is now completed. The designed system components and the schematic diagram are shown in Table 3 and Fig. 5, respectively.

Table 3. The designed system components

S/N	System Major Components	Quantities and combinations
1	PV module: 450 Wp/35 V monocrystalline	800 (200 strings of 4 modules)
2	Battery: 220 Ah/12 V tubular	1,200 (300 in parallel, 4 in series)
3	Charge controller: 5.8 kW/48 V/100 A MPPT	50
4	Inverter: 50 kW/48 Vdc/220 Vac sine wave	10

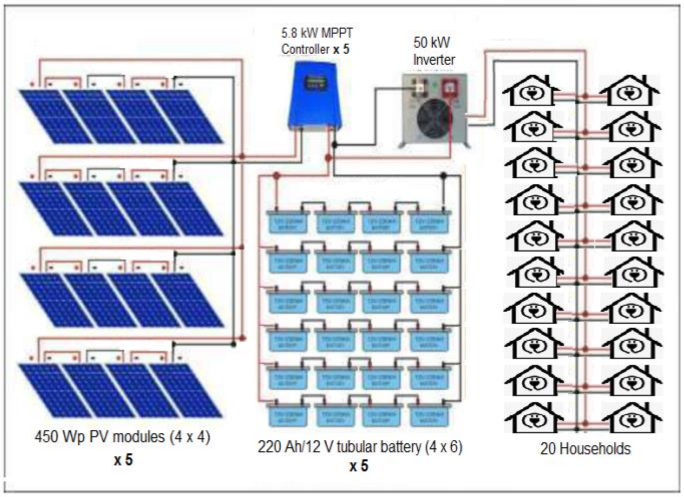


Fig. 5. Schematic diagram of one of ten units of the designed PV solar power plant

2.5 Technical and Economic Simulation

With the design completed, the technical simulation was done via the "Run Simulation" feature of the software. The software now generated the technical performance data of the designed power plant. This was saved. The economic evaluation was done by opening the economic evaluation feature and keying in the price in dollars of all the system components and accessories as shown in Table 4. The operating cost which includes the projected repairs and cleaning costs, and provision for battery bank replacement were also inputted as shown in Table 5. The electricity tariff was fixed at 0.15 USD/kWh. The economic performance data of the power plant was then generated with the financing set at 100% own fund (that is 0% loan financing). The result was saved. The evaluation was repeated with the loan financing set at 50% and 80%, respectively. The loan repayment period and annual interest were fixed at 5 years and 12%, respectively. The results were also saved.

Table 4. Installation costs

S/N	**System Components, Accessories, and Services**	**Quantity**	**Unit Price ($)**	**Total ($)**
1	PV module: 450 Wp/35 V monocrystalline	800	135	108,000
2	Battery: 220 Ah/12 V tubular	1,200	200	240,000
3	Charge controller: 5.8 kW/48 V/100 A MPPT	50	200	10,000
4	Accessories, Fasteners set	800	15	12,000
5	Wiring	10	50	500
6	Combiner box	10	10	100
7	Monitoring system, Displays	10	10	100
8	Surge Arrestor	10	20	200
9	Studies and analysis	1	500	500
10	Inverter: 50 kW/48 Vdc/220 Vac sine wave	10	2,000	20,000
11	Installation	1	7,950	7,950
			Total	**399,350**

Table 5. Operating costs

S/N	**System Services**	**Yearly cost ($/yr)**	**No. of Years**	**Total ($)**
1	Provision for battery replacement	12,000	20	240,000
2	Repairs	100	20	2,000
3	Cleaning	50	20	1,000
	Total	**12,150**	**20**	**243,000**

The important economic performance indices determined include the levelized cost of energy, the payback period, and the return on investment. The Levelized Cost of Energy (LCOE) is the cost of the produced energy in kWh. It takes into account the present value of future cash flows by applying a discount rate. It is calculated by the PVsyst software using the formula:

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (23)$$

where I_t = Investment and expenditures for the year (t), M_t = Operational and maintenance expenditures for the year (t), E_t = Electricity production for the year (t), r = Discount rate that could be earned in alternative investments, and n = Lifetime of the system. The Net Present Value (NPV) is the difference between the present value of cash inflows and the present value of cash outflows over a period which is determined using Equation 24:

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+r)^t} \quad (24)$$

where R_t = Net balance (income – expenses) for the year (t), r = Discount rate that could be earned in alternative investments, and n = Lifetime of the system. The payback period is the duration in years required to recover the cost of the net investment. Return on investment (ROI) is the ratio of net benefit against the initial investment which measures system profitability. It is calculated from equation 25:

$$ROI = \frac{Net\ benefit\ at\ the\ end\ of\ lifetime}{Total\ investment} \quad (25)$$

3. Results and Discussion

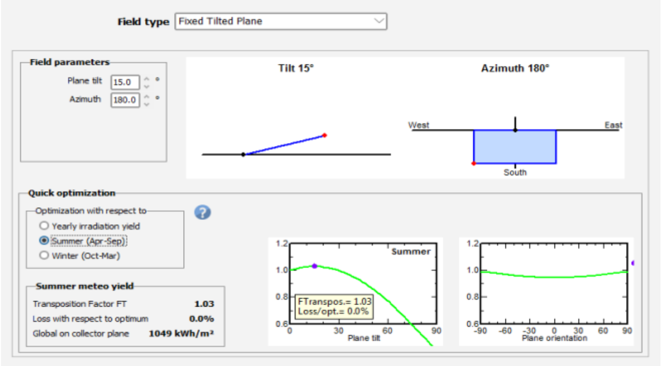
The orientation optimization, technical, and economic evaluation results generated by the PVsyst 7.3 software are hereby presented.

3.1 Orientation Optimization Results

The results of the orientation optimization test are presented in Table 6. From this table it can be seen that using the rainy season months of April to September for optimization (as done in this optimization test) and testing the performance of azimuths 0 and 180^0, the best-fixed plane tilt and azimuth for the location (with 1.03 transposition factor, 0% loss with respect to the optimum, and 1049 kWh/m^2 global irradiation on collector plane) are 15^0 and 180^0, respectively. The PV Syst orientation optimization guide at plane tilt/azimuth $15^0/180^0$ is shown in Fig. 6 while the horizon line drawing at fixed plane tilt/azimuth $15^0/180^0$ is shown in Fig. 7.

Table 6. Orientation optimization results

S/N	Azimuth (degree)	Plane tilt (degree)	Transposition factor	Loss with respect to the optimum	Global irradiation on collector plane (kWh/m^2)
1	0	0	1.00	0.0%	1021
2	0	5	0.99	-1.3%	1008
3	0	10	0.97	-3.1%	989
4	0	15	0.94	-5.6%	963
5	0	20	0.91	-8.7%	932
6	0	25	0.88	-12.4%	895
7	0	30	0.83	-16.6%	852
8	0	35	0.79	-21.1%	805
9	0	40	0.74	-26.1%	754
10	0	45	0.68	-31.5%	699
11	180	0	1.00	0.0%	1021
12	180	5	1.02	0.0%	1037
13	180	10	1.02	0.0%	1046
14	180	15	1.03	0.0%	1049
15	180	20	1.02	0.0%	1045
16	180	25	1.01	0.0%	1034
17	180	30	1.00	0.4%	1017
18	180	35	0.97	-2.80%	993
19	180	40	0.94	-5.7%	963
20	180	45	0.91	-9.2%	927



Field type Fixed Tilted Plane

Field parameters
Plane tilt 15.0 °
Azimuth 180.0 °

Quick optimization
Optimization with respect to
○ Yearly irradiation yield
● Summer (Apr-Sep)
○ Winter (Oct-Mar)

Summer meteo yield
Transposition Factor FT 1.03
Loss with respect to optimum 0.0%
Global on collector plane 1049 kWh/m²

Fig. 6. Orientation optimization guide at fixed plane tilt/azimuth $15^0/180^0$

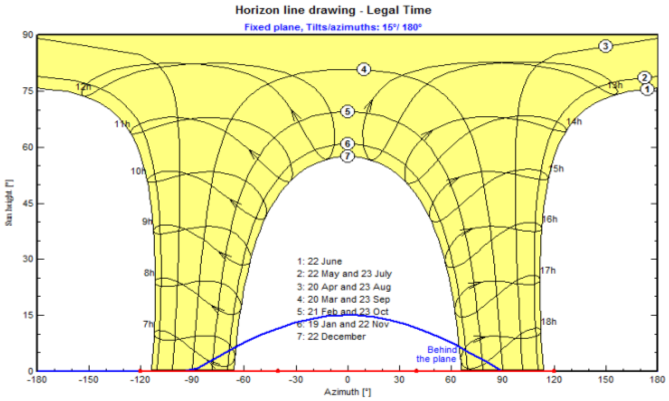


Fig. 7. Horizon line drawing at fixed plane tilt/azimuth $15^0/180^0$

3.2 PV System Energy Production and Losses

The system energy production and losses charts which include the Reference Incident Energy in Collector Plane (Yr), Normalized Production per installed kWp, Normalized Production and Loss Factors, Performance Ratio (PR), Incident Irradiation Distribution, Daily Input Output Diagram, and Daily Array Output Energy are presented in Figures 8, 9, 10, 11, 12, 13, and 14, respectively.

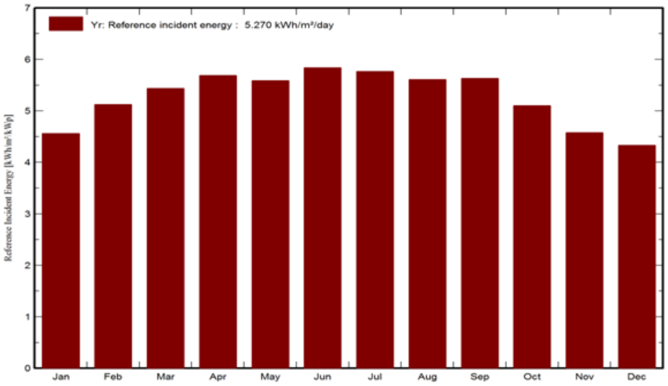


Fig. 8. Reference Incident Energy in Collector Plane

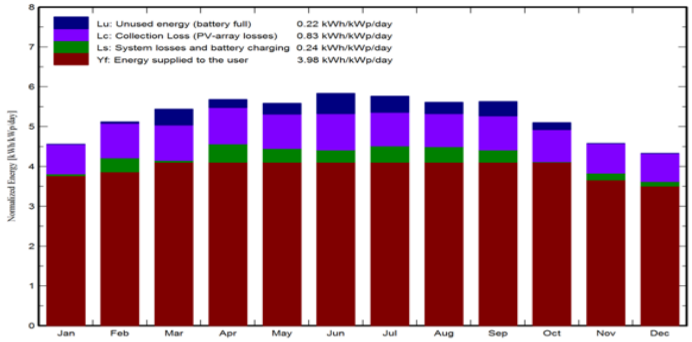


Fig. 9. Normalized Production (per installed kWp): Nominal Power 360 kWp

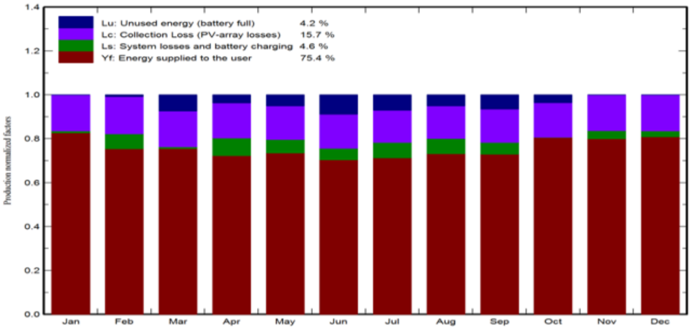


Fig. 10. Normalized Production and Loss Factors: Nominal Power 360 kWp

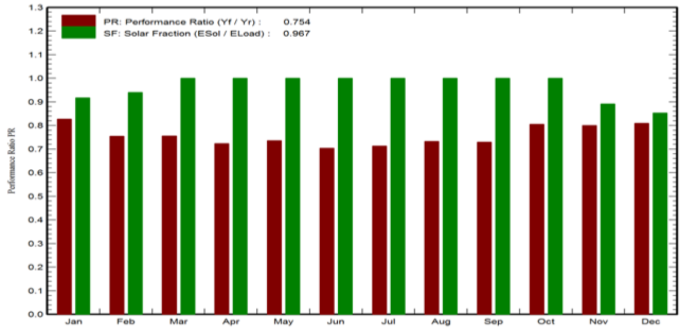


Fig. 11. Performance Ratio, PR and Solar Fraction, SF

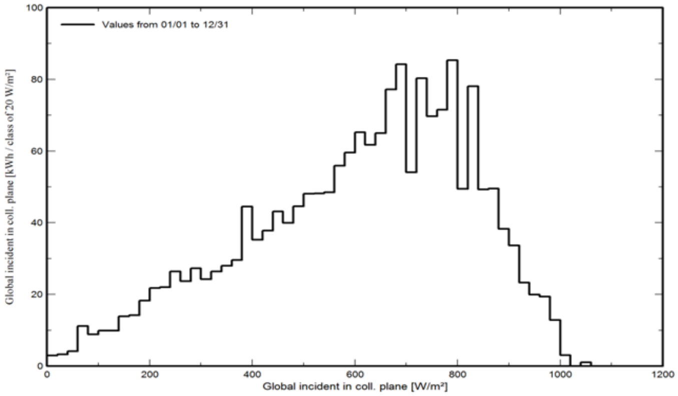


Fig. 12. Incident Irradiation Distribution

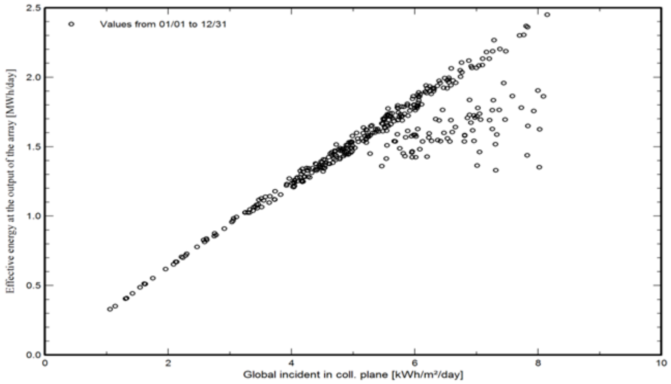


Fig. 13. Daily Input/Output Diagram

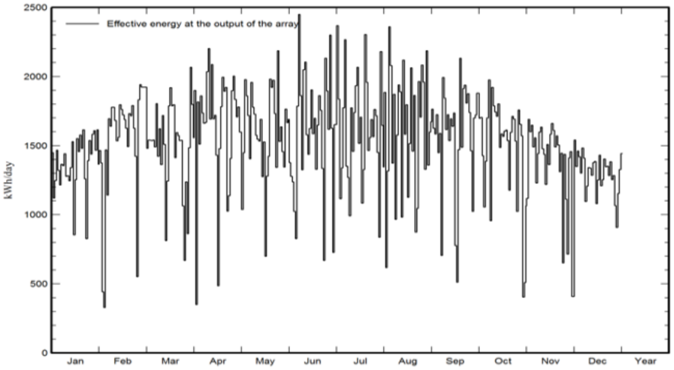


Fig. 14. Daily Array Output Energy

A glance at Figures 8, 9, and 10, shows that the average reference incident energy in the collector plane is 5.270 kWh/m^2/day. With this 5.270 kWh/m^2/day incident energy, a kilowatt-peak of the PV array will deliver 3.98 kWh/day (75.4%) of energy to the user. System losses and battery charging, PV array collection loss, and unused energy due to battery full will take the balance of energy as fol 0.24 kWh/kWp/day (4.6%), 0.83 kWh/kWp/day (15.7%), and 0.22 kWh/kWp/day (4.2%), respectively. From Fig. 11, the performance ratio, PR which is the ratio of energy supplied to the user, Yf to the reference incident energy, Yr (that is, Yf/Yr) is obtained as 0.754 (75.4%), while the solar fraction, SF which is the ratio of the energy supplied by the solar array, ESol to the energy needs of the user, ELoad (that is ESol/ELoad) is obtained as 0.967 (96.7%). Fig. 12 which depicts the incident irradiation distribution is realized by plotting the global incident energy in the collector plane (in kWh per class of 20 W/m^2) against the global incidence energy in the collector plane (in W/m^2). From Fig 13, it can be seen that the variation of the effective energy at the output of the array (in MWh/day) as against the global incident energy in the collector plane (in kWh/m^2/day) is linear at lower values of the incident energy but the linearity seizes from about 4.0 kWh/m^2/day of incident energy which can be as a result of the effects of higher PV array temperatures at such incident energy values. Fig. 14 shows that the highest peaks of the effective energy at the output of the array occur from April to September. This can be attributed to the orientation optimization done using those months. This trend can also be seen in Figures 8 and 11. The batteries' state of charge daily distribution and the system loss diagram are presented in Figures 15 and 16, respectively.

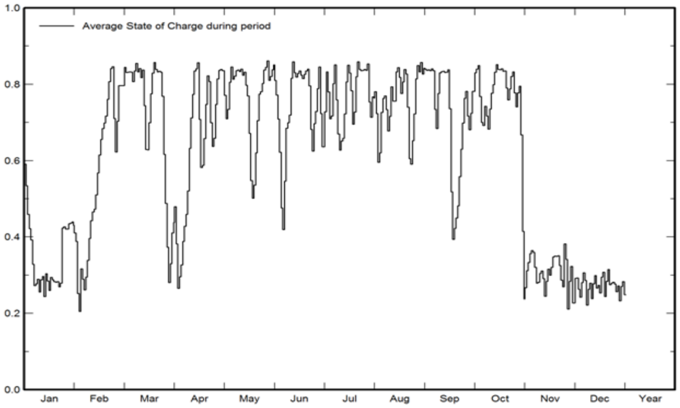


Fig. 15. State of Charge Daily Distribution

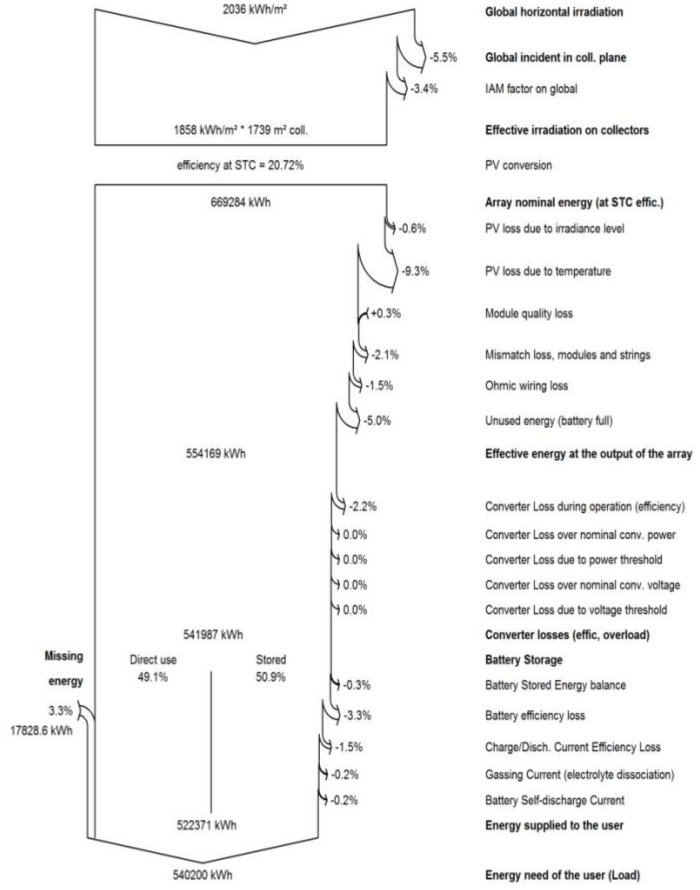


Fig. 16. Loss Diagram for the Power Plant

A summary of the technical simulation results and energy balances are presented in Table 7 while the system production and performance indices are extracted and presented in Table 8.

Table 7. PV System Energy Balances and Main Results

	Global horizontal irradiation (kWh/m²)	Effective Global irradiation on collector plane (kWh/m²)	Available Solar Energy (kWh)	Unused energy (battery full) (kWh)	Missing energy (kWh)	Energy supplied to the user (kWh)	Energy need of the user/load (kWh)	Solar fraction (ratio)
January	169.9	133.9	41660	0	3786	42094	45880	0.917
February	163.5	137.4	41933	334	2462	38978	41440	0.941
March	180.1	163.2	49809	4461	0	45880	45880	1.000
April	171.0	166.3	50452	2226	0	44400	44400	1.000
May	167.1	168.9	51686	3086	0	45880	45880	1.000
June	165.0	170.7	52140	5553	0	44400	44400	1.000
July	170.2	174.3	53811	4517	0	45880	45880	1.000
August	172.1	169.5	52234	3167	0	45880	45880	1.000
September	175.5	164.3	50567	3915	0	44400	44400	1.000
October	174.8	152.1	46927	1993	0	45880	45880	1.000
November	162.0	130.6	40478	0	4833	39567	44400	0.891
December	164.3	126.6	39591	0	6747	39133	45880	0.853
Year	2035.5	1857.8	571288	29302	17829	522371	540200	0.967

Table 8. System Production and Technical Performance Indices

System Production	Loss of Load	Battery Aging (State of Wear, SOW)
Available Energy = 571,288 kWh/year	Time Fraction = 2.7%	Cycles SOW = 93.5%
Used Energy = 522,371 kWh/year	Missing Energy = 17,829 kWh/year	Static SOW = 90.0%
Excess (Unused) Energy = 29,302 kWh/year		Battery lifetime = 10.0 years
Performance Ratio, PR = 75.43%		
Solar Fraction, SF = 96.70%		

With a performance ratio of 75.43% and a loss of load time fraction of 2.7%, the system will be highly efficient and reliable as it will underperform for only 2.7% of the time. The month with the highest missing energy is December while eight months (from March to October) have no missing energy.

3.3 Economic Evaluation Results

The economic evaluation results which include the no loan financing, 50% loan financing, and 80% loan financing results are presented in Figures 17, 18, 19, and 20. The important economic results are summarized in Table 9.

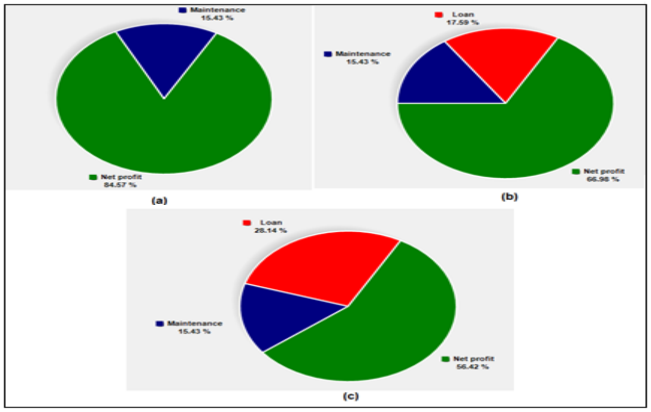


Fig. 17. Income allocation for (a) 0% loan financing, (b) 50% loan financing, and (c) 80% loan financing

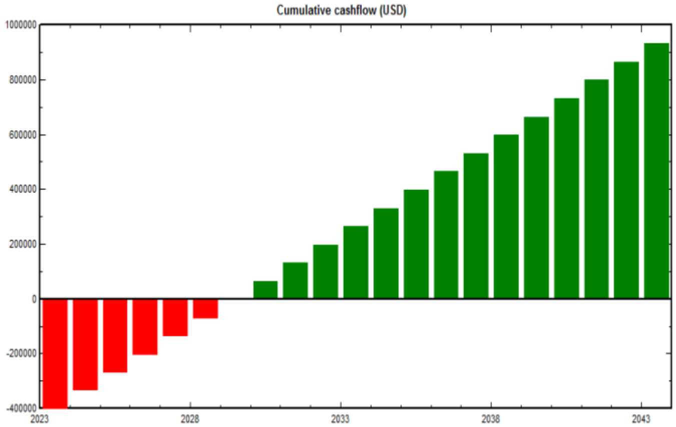


Fig. 18. Cumulative cash flow for 0% loan financing

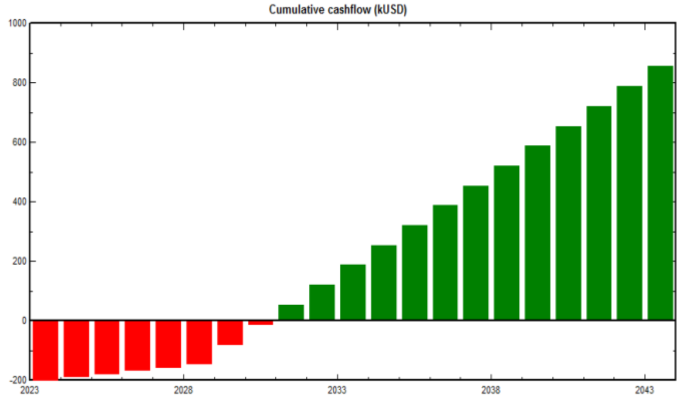


Fig. 19. Cumulative cash flow for 50% loan financing

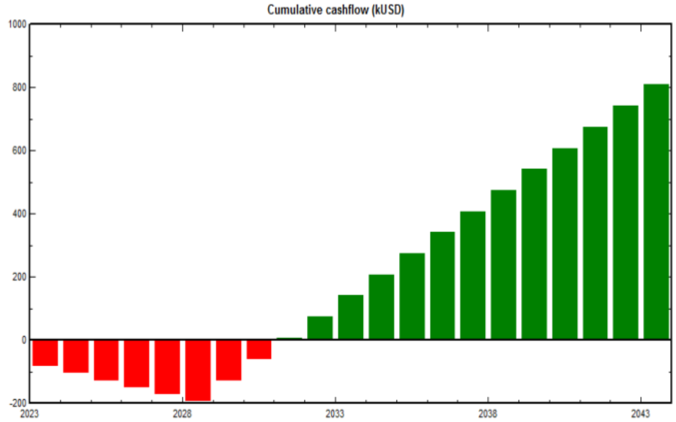


Fig. 20. Cumulative cash flow for 80% loan financing

Table 9. Economic evaluation results summary

Evaluation with 0% Loan Financing	Evaluation with 50% Loan Financing	Evaluation with 80% Loan Financing
Installation cost financing	**Installation cost financing**	**Installation cost financing**
Own funds = 399,350 USD	Own funds = 199,675 USD	Own funds = 79,870 USD
Loans = 0.00 USD	Loans = 199,675.00 USD	Loans = 319,480.00 USD
Total: 399,350 USD	Total: 399,350 USD	Total: 399,350 USD
Expenses	**Expenses**	**Expenses**
Operating cost (OPEX) = 12,150.00 USD/year	Operating cost (OPEX) = 12,150 USD/year	Operating cost (OPEX) = 12,150 USD/year
Loan annuities = 0.00 USD/year	Loan annuities for 5 yrs = 55,391.79 USD/year	Loan annuities for 5 yrs = 88,626.86 USD/year
Total yearly cost = 12,150.00 USD/year	Total yearly cost = 25,997.95 USD/year	Total yearly cost = 34,306.72 USD/year
Levelized cost of energy, LCOE = 0.0612 USD/kWh	Levelized cost of energy, LCOE = 0.0686 USD/kWh	Levelized cost of energy, LCOE = 0.0730 USD/kWh
Specific cost = 1.11 USD/Wp	Specific cost = 1.11 USD/Wp	Specific cost = 1.11 USD/Wp
Return on Investment	**Return on Investment**	**Return on Investment**
Energy tariff = 0.15 USD/kWh	Energy tariff = 0.15 USD/kWh	Energy tariff = 0.15 USD/kWh
Net present value, NPV = 932,230.45 USD	Net present value, NPV = 854,946.51 USD	Net present value, NPV = 808,576.15 USD
Payback period = 6.0 years	Payback period = 7.2 years	Payback period = 7.9 years
Return on investment, ROI = 233.4%	Return on investment, ROI = 214.1%	Return on investment, ROI = 202.5%

All the economic indices of the three financing considerations show that the project is highly feasible. The levelized cost of energy which is 0.0612 USD/kWh, 0.0686 USD/kWh, and 0.0730 USD/kWh for the 0%, 50%, and 80% loan financing options, respectively, are lower than the current subsidized electricity tariff in Nigeria which is about 0.08 USD/kWh. This means that even if the generated energy is sold at this subsidized rate, the system will still be feasible.

4. Conclusion

The technical and economic feasibility of a standalone PV solar power plant for a typical 200 bungalow housing estate in Abuja, Nigeria was studied via simulated results obtained using PVsyst 7.3 software. The design shows that with a global horizontal irradiation of 2.04 MWh/m^2/year reaching Abuja, Nigeria, a 360 kWp PV system is needed to supply the energy needs of the estate with an energy demand of 1,480 kWh/day.

The system will produce a total of 571,288 kWh (approximately 571 MWh) of electric energy per year with a performance ratio of 75.4 % and a solar fraction of 96.7%.

The proposed project is highly feasible as the economic evaluation results show that the system installation cost is 399,350 USD at a specific cost of 1.11 USD/kWp, and the net present value (NPV) is positive at 932,230.45 USD, 854,946.51 USD, and 808,576.15 USD, respectively for the three cases of 0%, 50%, and 80% loan financing.

With an energy tariff of 0.15 USD/kWh, the return on investment, payback period, and levelized cost of energy were determined as 233.4%, 6.0 years, and 0.0612 USD/kWh, respectively for the 0% loan financing case; 214.1%, 7.2 years, and 0.0686 USD/kWh, respectively for the 50% loan financing case; and 202.5%, 7.9 years, and 0.0730 USD/kWh, respectively for the 80% loan financing case.

The government of Nigeria should encourage and promote the adoption of solar energy as the source of electricity for the estates in Abuja and its environs as this study has revealed that it is highly profitable. Solar energy developers should also use the results of this study to promote their business in Abuja and Nigeria in general.

Further studies should be done to ascertain the feasibility of both standalone and integrated PV systems at other locations that have not been covered. Also, more development work should be done to further improve the efficiency of PV systems.

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