

# Design and Techno-economic Simulation of a Standalone PV Solar Power Plant for a Typical Housing Estate in Owerri, Nigeria

## ABSTRACT

Most, if not all, of the estates in Owerri, Nigeria are planned without recourse to the United Nations Sustainable Development Goals (SDG) envisions 2030's goals 7 and 11. SDG goal 7 (on affordable and clean energy) and goal 11 (on sustainable cities and communities) envision a world by 2030 where there will be universal access to affordable, reliable, and modern energy services; a substantial increase in the share of renewable energy in the global energy mix, etc. This research was done to depict the feasibility of a photovoltaic (PV) power plant for estates in Owerri, Nigeria. A standalone PV solar power plant for a typical 200 bungalow housing estate in Owerri, Nigeria was designed and simulated to study its techno-economic feasibility using PVSyst 7.3 simulation software. The study revealed that with a global horizontal irradiation of 4.70 kWh/m<sup>2</sup>/day reaching Owerri, Nigeria, a 468 kWp PV system is required to supply the electricity needs of an estate with an energy demand of 1,480 kWh/day. The system will generate a total of 615,168 kWh of electric energy in a year with a performance ratio of 70.4 % and a solar fraction of 96.8%. The designed PV solar power plant is highly feasible as the obtained results from the economic simulation showed that the system's installation cost is 466,970 USD at a specific cost of 1.0 USD/kWp, and the net present value (NPV) is positive at 842,699.16 USD, 752,219.11 USD, and 698,107.07 USD, respectively for the 0%, 50%, and 80% loan financing cases. With an energy tariff of 0.15 USD/kWh, the return on investment, payback period, and levelized cost of energy were determined as 180.5%, 7.2 years, and 0.0698 USD/kWh, respectively for the 0% loan financing case.

*Keywords: housing estates; UN SDG; solar power plant; PV system; PVSyst simulation; economic evaluation.*

## 1. INTRODUCTION

A look around Owerri and Nigeria, in general, shows a lot of existing, under construction, and proposed housing estates. This is made possible through the efforts of cooperative societies, professional bodies, real estate companies, and the government. Fig. 1 shows some housing estates in Owerri, Nigeria. But it is worrisome that most, if not all, of these estates, are planned without recourse to the United Nations (UN) Sustainable Development Goals (SDG) envision 2030's goals 7 and 11.



Open Gate Estate Owerri



Arugo Gardens Estate



FG Nig. Sponsored Estate along Port Harcourt Road, Owerri

Fig. 1. Some housing estates in Owerri Nigeria

The UN SDG goal 7 (on affordable and clean energy) and goal 11 (on sustainable cities and communities) envision a world by 2030 where there will be: universal access to affordable, reliable, and modern energy services; a substantial increase in the share of renewable energy in the global energy mix; doubled global rate of improvement in energy efficiency; enhanced international cooperation to facilitate access to clean energy research and technology; expanded infrastructure for supplying modern and sustainable energy services for all in developing countries; a substantial number of cities and human settlements adopting and implementing policies and plans towards inclusion, resource efficiency, mitigation and adaptation to climate change; etc[1,2]. This vision will not materialize on its own but requires the efforts of all and sundry to make it a reality. One of the ways to make these housing estates UN SDG Envision 2030 compliant is to incorporate a standalone PV solar power plant in the plan of these estates to provide the electricity needs of the residents. This will drastically reduce the carbon footprint of the housing estates. Moreover, both local and international assistance can be sought to enable the installation of such a renewable energy power plant as there exist soft loans and grants for that purpose. Such funds that can be accessed include the Six Billion Naira Bank of Industry (BOI) Solar Energy Fund [3], African Development Bank's Sustainable Energy Fund for Africa [4], and Rural Electrification Agency's Standalone Solar Home Systems for Households and MSMEs Output Based Fund [5]. This work aims at exposing the benefits of installing a standalone PV solar power system for a housing estate, thereby arousing the interest of current and future estate dwellers, developers, and governments, in solar energy.

### **1.1 Factors Limiting PV Systems Deployment in Nigeria**

Nigeria is blessed with abundant solar energy potential waiting to be harnessed. This is because she is positioned at a location with relatively high solar radiation intensity and longer average daily sunshine hours than most other countries with better solar energy utilization records [6]. Even the coastal areas of Nigeria have great solar energy potential [7].

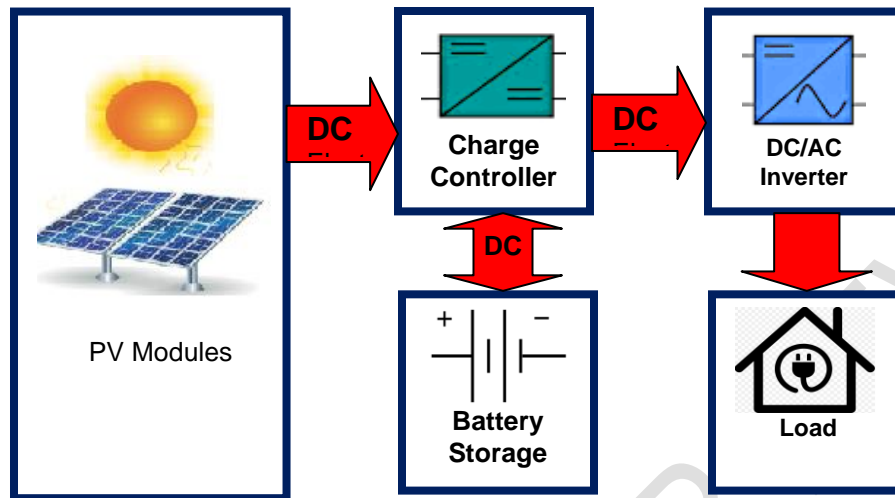
Many Nigerians are unaware of the merits of having PV solar energy systems installed. This has been identified as a major obstacle to the widespread adoption of PV systems in Nigeria [8]. Technical issues such as early component failures caused by poor design and lack of maintenance, as well as their discouraging impact on potential new users, are other factors limiting the penetration of PV solar systems in Nigeria. The inadequate human capacity building and related training in solar energy development, installation, and maintenance in the country is to blame for this [9]. There are also other challenges to the widespread deployment of solar energy systems in Nigeria. These include poverty, which makes it difficult for most of the population to afford the high initial costs of installing a PV system, and concerns about the high level of insecurity in the country, which leads to theft and vandalism [9]. To tackle these challenges and create a favorable condition for the widespread deployment of PV solar energy systems in Nigeria, both the government and citizens have roles to play. Local production of PV panels and system components to drive down the installation costs, capacity development training, and more research and publications in the area of solar PV systems will go a long way in addressing these identified issues [10].

### **1.2 Solar PV Power Plant**

Solar energy can be utilized for electricity generation via solar thermal and PV systems. Solar thermal electricity generation systems use solar concentrators to focus sun rays onto a water boiler to produce steam that drives a steam turbine. The turbine in turn drives an alternator to generate electric power. On the other hand, a PV system uses PV modules to directly convert solar radiation to direct current (DC) electricity via the photovoltaic principle. The DC electricity can be converted to alternating current (AC) electricity by the use of inverters.

The solar energy electricity generating system can be designed as a hybrid power plant, grid-connected power plant, or a standalone power plant. In the hybrid power plant, another energy source like wind, hydro, or even fossil fuel energy generator is added to complement the solar energy. A grid-connected solar power plant has its AC output connected to an electricity grid via a distribution control board which also supplies electricity to the AC appliances in the house. The grid-connected system does not require battery storage as the grid supplies electricity to the house to complement the solar energy system in

times of insufficient power generation, and also draws from it when the solar-generated electricity is more than the electricity needs of the house. On the other hand, in the standalone power plant, the only energy source is solar. A storage system is included in most cases to mitigate the effect of solar energy resource intermittency. A charge controller is also included to control the charging and discharging of the batteries to avoid over-charging or over-discharging which can damage the batteries. The batteries must have enough capacity to store energy during the day to complement or supply the needed energy in times of low or no solar radiation reaching the system [11]. A standalone PV solar power plant's block diagram is depicted in Fig. 2.



**Fig. 2. A standalone PV solar power plant's block diagram**

To design a PV solar power plant, some basic parameters are needed. These include the historical solar irradiation data of the proposed installation site, the loads' wattage and operational times, the input DC voltage and the output AC voltage of the system, the technical parameters of the PV modules like the peak wattage, open circuit voltage, short circuit current, maximum power point voltage and current, and efficiency, and the efficiency of the balance of system components like charge controllers and inverters. With these parameters, the following steps are taken to design a solar PV system: determine the total load current and operational time; compensate for system losses; determine the solar irradiation in daily equivalent sun hours (ESH) which is realized by dividing the historical average daily solar irradiation of the site by one-sun irradiance ( $1 \text{ kW/m}^2$ ); determine total solar array current requirements; determine optimum module arrangement for solar array; and determine battery size for the recommended reserve time called days of autonomy (DOA) [11]. The design can be done using design formulas to manually calculate and determine the component sizes and ratings. Softwares that can be employed to design and/or simulate the performance of solar PV systems also exist. For the simulation softwares that do not incorporate design features, the designer will have to manually estimate the components' sizes using the design formula before employing the softwares to simulate the performance of the designed system. The solar PV power plant design formula and components sizing procedure have been presented in our earlier publication [12].

### 1.3 Softwares for Solar PV Systems Design and Simulation

Some of the PV systems design and simulation softwares include RETScreen, PV F-Chart, SolarDesign Tool, INSEL, TRNSYS, Solar Advisor Model (SAM), PVSyst, SolarPro, PV-DesignPro-G, and HOMER [13]. PV software simulators in the market have different advantages and limitations following the specific areas of interest of the makers [14]. RETScreen, PVSyst, SolarPro, and HOMER are the most used PV system simulation softwares due to their features and versatility.

RETScreen is a decision-support software developed by the Government of Canada. It has the needed database [which is sourced from the World Radiation Data Center (WRDC), National Aeronautics and

Space Administration (NASA), and about 18 other sources] for the simulation of any clean energy project in virtually any location across the world [13]. It can be used to do energy production and savings estimation, cost assessment, emission assessment and reduction, financial viability assessment, and risk assessment for different renewable energy types and energy-efficient technologies.

PVSyst is developed by the University of Geneva. It offers a wide range of features that boost its overall usefulness and outreach [15]. It can be used for the complete design and simulation of both grid-connected and standalone solar PV systems [16,17]. It sources metrological data from many stations across the world. PVSyst also has a database for solar modules and other solar PV system parameters from a large number of producing companies for easy systems design and simulation [13]. The large components database also enables economic evaluation and payback period estimation.

SolarPro helps to estimate the amount of electricity produced by a solar PV system, taking into cognizance the values of latitude, longitude, and weather conditions of the installation site which helps to improve the accuracy of the simulation results. It also produces simulation results on shadow influence due to surrounding buildings and objects [13].

HOMER (Hybrid Optimization of Multiple Energy Resources) software was originally developed at the National Renewable Energy Laboratory (NREL) of the U.S. Department of Energy but is now enhanced and distributed by HOMER Energy. It is used in the design, simulation, and optimization of both standalone and hybrid systems. Its simulation results have been shown to be more accurate than those of RETScreen[18].

#### **1.4 Review of Related Literature**

Studies on solar energy systems including the design and simulation of PV solar systems have been carried out in different parts of the world and at different times for the purposes of feasibility studies, performance characterization, optimization, awareness creation, etc. Performance characterization was done on a grid-connected 20 MW photovoltaic power plant operating in a hot climate using real-site obtained data analysis and simulations with RETScreen and HOMER softwares[18]. The results revealed that the HOMER simulation performed better than the RETScreen simulation as the HOMER results were quite close to the site measurement results (with a 5.1% deviation) while the RETScreen results deviated by about 14%. The temperature was also observed to affect the performance of the PV system. In another comparative study of the two softwares done at a location in Thailand, HOMER also outperformed RETScreen by about 2.5% [19].

A design and feasibility study was carried out using RETScreen simulation to determine the contribution of a 1MW grid-connected solar PV system in meeting the energy needs of a University in Ghana [20]. The results showed that with the 4.30kWh/m<sup>2</sup>/day average daily solar irradiation of the area, the PV system will generate 1,159MWh of electricity in a year which is about 12.5% of the electricity needs of the University. The study also revealed that the PV system will save the planet about 850 tonnes of CO<sub>2</sub> emissions. The energy payback period was estimated at 45 years with the existing bulk electricity generation charge of about US\$0.08/kWh and a total system cost of about US\$5/Wp.

Faiz et al. [21] used PVSyst software to model and analyze a 3 MW Solar PV Plant at Islamia University of Bahawalpur, Pakistan. With an average daily solar irradiation of 5.9 kWh/m<sup>2</sup>/day, the study estimated the PV system electricity production of 4,908 MWh/year. The cost of the electricity produced was estimated at 0.11 US \$/kWh which is less than the prevailing conventional energy tariff of 0.18 \$/kWh in Pakistan. In another PV system study in Pakistan, A. Iqbal and M. Iqbal [22] simulated the performance of a stand-alone PV system for a rural house in Pakistan using HOMER Pro. The simulation result showed that with an installation cost of \$9,650 for a 5.8 kWp PV system, the electricity generation cost would be \$0.199/kWh. This is larger than the 0.11 US \$/kWh generation cost for the 3 MW Solar PV Plant and shows that the bigger the solar PV plant, the less the energy production cost.

The effect of varying the solar panels' tilt angle was investigated using PVSyst 7.2 simulation on a 250 kWp grid-connected solar PV plant in Pune, India [23]. The results show that with monthly tilt angle

variations of 47, 45, 23, 5, 0, 0, 0, 0, 15, 31, 44, and 49 degrees, the PV system will supply 393,246 kWh of electricity per month to the grid which is 15,744 kWh higher than the 377,502 kWh electricity to be generated per month if the angle is fixed all year round at 20 degrees. Also using PVSyst simulation, the performance, and degradation of a large-scale PV power plant (1 MWp) located in the coastal region of Andhra Pradesh, India was studied [24]. The energy generated per year was estimated at 1,685 MWh, with the performance ratio and light-induced degradation estimated at 87.9% and -2.7 %/year, respectively. Lee-Jone [25] studied the feasibility of building integrated solar PV and wind power systems on the Swedish Island of Gotland. The RETScreen simulation results indicated that the PV part of the system was not cost-effective while the wind power part was very feasible in the region.

The performance and economic viability of a grid-connected rooftop solar PV system in Vietnam was studied and the PVSyst simulation results show that an 8.36 kWp system will produce 11,106 kWh of electricity in a year, saving the planet about 8.7 tons of CO<sub>2</sub> per year [26]. The cost of installing the system, annual average system efficiency, and energy payback period were also estimated as 5,691.7 USD, 81.17%, and 12 years, respectively. In a similar study in Indonesia using PVSyst and RETScreensoftwares, it was found that with an average daily solar radiation of 5.17 kWh/m<sup>2</sup>/day available in Surabaya, a 1 kWp grid-connected PV system could send about 1.3 MWh /yr electricity to the grid on the average [27]. The energy payback period was found to be 17.6 years at the prevailing feed-in tariff but if the government could increase the feed-in tariff to USD 0.25/kWh, the energy payback period would reduce to 6.5 years. The greenhouse gas savings of the system were also estimated to be 1.66 kg of SO<sub>2</sub>, 3.46 kg of NO<sub>x</sub>, 1295 kg of CO<sub>2</sub>, and 91 kg of ash per year. Windarta et al. [28] also used PVSyst and RETScreensoftwares to design and study the technical and economic feasibility of a 1,215 Wp grid-connected PV system for a household in the city of Semarang, Indonesia. The annual energy yield of the systems was found to be 1,898 kWh while the Discounted Payback Period (DPP) of the systems was estimated to be 10.07 years.

**PV systems'** performance and economic viability studies have also been carried out at some locations in Nigeria. Ani V. and Ani E. [29] designed and simulated the performance of a PV-Diesel hybrid power plant for a 254 kWh/d Base Transceiver Station located in Nkanu-West Local government area of Enugu State, Nigeria. The HOMER simulation results show that with an annual average solar radiation of 4.92 kWh/m<sup>2</sup>/d of the location, the 10.7 kWp PV system would contribute 16,024 kWh/yr of electricity which is 14% of the total energy need of the station. In another HOMER simulation study for a PV-Biomass hybrid system proposed at Unwana community in Ebonyi state, Nigeria, a 4.6kWp PV system would contribute 5,771 kWh/yr of electricity which is 6.3% of the total electricity demand of the community with annual solar irradiation of 4.71 kWh/m<sup>2</sup>/day [30]. PV system was also found to be highly feasible in Abuja, Nigeria as a PVSyst simulation showed that, with the 2.04 MWh/m<sup>2</sup>/year global horizontal irradiation reaching Abuja, a 360 kWp PV system is required to supply the electricity needs of an estate having 1,480 kWh/day electric energy demand. With a 0.15 USD/kWh energy tariff, the return on investment, payback period, and levelized cost of energy for the Abuja 360 kWp PV system were found to be 233.4%, 6.0 years, and 0.0612 USD/kWh, respectively for the 0% loan financing case [31]. In another research, a practical evaluation of the performance of a PV module under the southern Nigeria climate showed that a 160.0 Wp PV module would generate a maximum of 100.6 W which means a maximum capacity factor of 63% [32].

## 2. MATERIAL AND METHODS

PVSyst 7.3 design and simulation software was chosen for this work because of its ability to do both technical and economic simulations. It has a metrological database **obtained** from NASA and **some** other stations across the world. A second attractive feature of this software is its large database of components which helps in the system design and economic evaluation.

### 2.1 PV System Design

The bungalow housing estate is to have 200 units of 3-bedroom flat bungalows. The estimated daily energy demand of the estate is given in Table 1.

**Table 1. The estimated daily energy demand of the estate**

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	LED Lamp1	10 W	10	100 W	10	1,000 Wh/d	200 kWh/d
2	LED Lamp2	5 W	04	20 W	10	200 Wh/d	40 kWh/d
3	PC/TV	100 W	05	500 W	06	3,000 Wh/d	600 kWh/d
4	Fridge/ Freezer	1,200 Wh/d	01	1,200 Wh/d	24	1,200 Wh/d	240 kWh/d
5	Blender/Wash ing machine	1,000 W	01	1,000 Wh	01	1,000 Wh/d	200 kWh/d
6	Electric Iron	1,000 W	01	1,000 Wh	01	1,000 Wh/d	200 kWh/d
						<b>Total</b>	<b>1,480 kWh/d</b>

With the energy demand information ascertained, the geographical site data of the proposed estate location was selected from NASA's Surface Meteorology and Solar Energy (NASA-SSE) database of the PVsyst software as shown in Table 2. The plane tilt and Azimuth were selected following the software's orientation optimization guide. The orientation optimization was done considering the rainy season months of April to September. The azimuth was **set** at  $0^{\circ}$  and  $180^{\circ}$  while the plane tilt was varied from  $0^{\circ}$  to  $45^{\circ}$ , **respectively** for the two azimuths. The transposition factor, loss with respect to optimum, and global irradiation on the collector plane were noted for each plane tilt. From this test, the **optimal** plane tilt and azimuth were selected as  $20^{\circ}$  and  $180^{\circ}$ , respectively.

The daily energy demand data of the estate as given in Table 1, was then keyed into the user's needs data input of the software, and the hourly distribution of the energy demand was defined as shown in Fig. 3. Also, the daily global consumption was generated as shown in Fig. 4.

**Table 2. Monthly **Metrological** Data of Owerri, Nigeria **sourced** from NASA-SSE Data Base**

	Global horizontal irradiation (kWh/m <sup>2</sup> /day)	Horizontal diffuse irradiation (kWh/m <sup>2</sup> /day)	Temperature ( <sup>o</sup> C)
January	5.53	1.73	25.4
February	5.59	1.97	25.8
March	5.32	2.22	25.7
April	5.09	2.27	25.8
May	4.72	2.18	25.7
June	4.31	2.11	25.8
July	3.85	2.13	24.1
August	3.77	2.20	23.9
September	3.94	2.27	24.2
October	4.27	2.17	24.5
November	4.84	1.95	24.7
December	5.29	1.71	24.7
<b>Year</b>	<b>4.70</b>	<b>2.08</b>	<b>24.9</b>

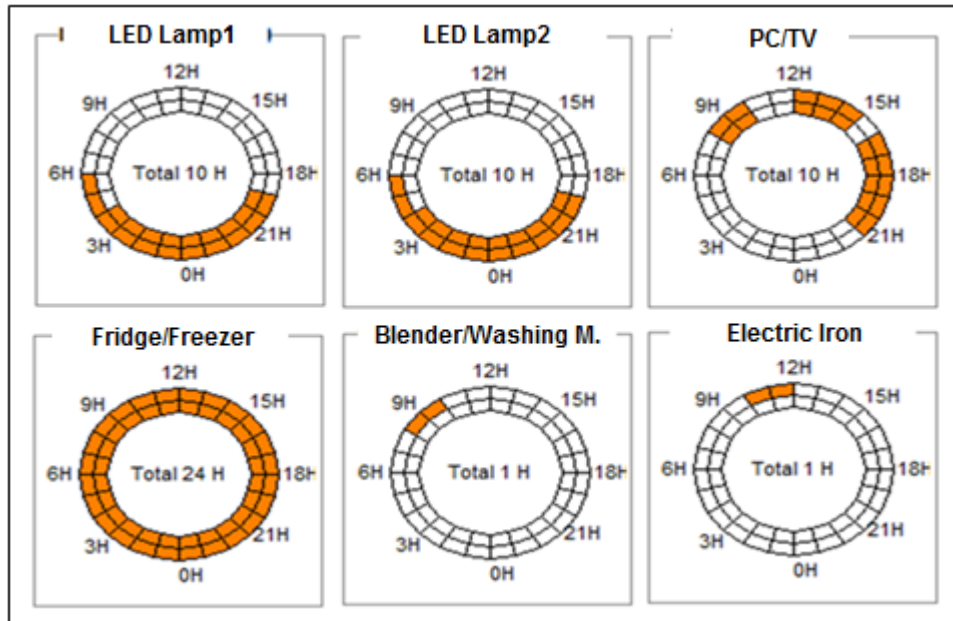


Fig. 3. The energy demand hourly distribution

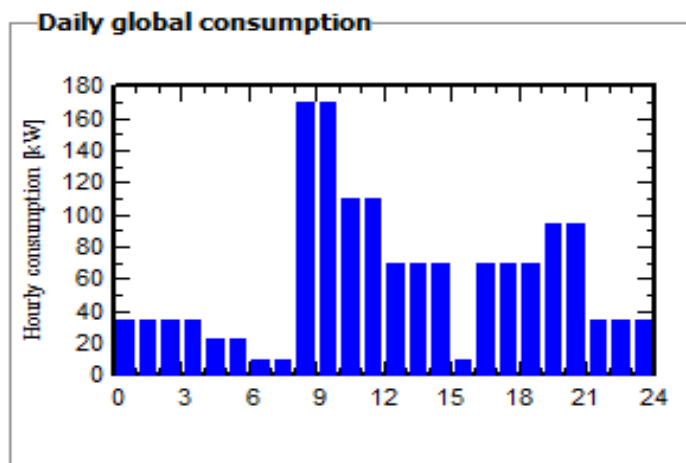


Fig. 4. Daily global consumption

The next stage was the pre-sizing stage where the desired system's pre-sizing conditions are chosen. The system's pre-sizing parameters which include battery voltage, Loss-of-load (LOL) probability, and days of autonomy were chosen as 48 V, 10%, and 2 days, respectively. The type and model of the battery to be used were also selected from the battery database. With these parameters defined, the needed number and arrangement of batteries to meet the set conditions were generated by the software.

Then it was the stage for the PV array, charge controller, and inverter sizing. The needed PV module, charge controller, and inverter were chosen from the software's database. The software then produced the optimum quantities and combinations of these components needed to realize the design objectives. The realized system components and combinations are given in Table 3.

Table 3. **Components** of the designed system

S/N	System Major Components	Quantities and combinations
1	PV module: 450 Wp/35 V monocrystalline	1,040 (260 strings of 4 modules)
2	Battery: 220 Ah/12 V tubular	1,320 (330 in parallel, 4 in series)
3	Charge controller: 5 kW/48 V/100 A MPPT	80
4	Inverter: 50 kW/48 Vdc/220 Vac sine wave	10

## 2.2 System Simulation

With all the major components of the system now specified, the technical simulation was done. Afterward, an economic evaluation of the systems was done by specifying all the major and minor components, accessories, services, and their costs as given in the installation and operating costs Tables 4 and 5. The financial parameters and electricity tariff were also specified. The economic evaluation was done for three financing cases of no loan, 50% loan, and 80% loan financing. The 80% loan financing is the maximum that can be obtained from the Bank of Industry, Nigeria (our reference funding institution) for solar energy deployment.

Table 4. Installation costs

S/N	System Components, Accessories, and Services	Quantity	Unit Price (\$)	Total (\$)
1	PV module: 450 Wp/35 V monocrystalline	1,040	135	140,400
2	Battery: 220 Ah/12 V tubular	1,320	200	264,000
3	Charge controller: 5 kW/48 V/100 A MPPT	80	200	16,000
4	Accessories, Fasteners set	1,072	15	16,080
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	9154	9,154
			<b>Total</b>	<b>466,970</b>

Table 5. Operating costs

S/N	System Services	Yearly cost (\$/yr)	No. of Years	Total (\$)
1	Provision for battery replacement	13,200	20	264,000
2	Repairs	100	20	2,000
3	Cleaning	50	20	1,000
<b>Total</b>		<b>13,350</b>	<b>20</b>	<b>267,000</b>

The levelized cost of energy and other important economic performance indices of the system which include the net present value, the return on investment, and the payback period were determined. The Levelized Cost of Energy (LCOE) **represents** the cost of the produced energy in kWh. It applies a discount rate to take into cognizance the present value of future cash flows. The PVsyst software determines the LCOE with the formula,

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

where  $I_t$  is the Investment and expenditures for the year (t),  $M_t$  is the operational and maintenance expenditures for the year (t),  $E_t$  is the electricity production for the year (t),  $r$  is the discount rate that could be earned in alternative investments, and  $n$  is the lifetime of the system. The Net Present Value (NPV)

represents the disparity between the present value of cash outflows and inflows over a period of time. It is calculated with the formula,

$$NPV = \sum_{t=1}^n \frac{R_t}{(1+r)^t} \quad (2)$$

where  $R_t$  is the net balance (income – expenses) for the year (t), r is the discount rate that could be earned in alternative investments, and n is the lifetime of the system. The payback period means the period in years needed to recover the net investment cost. Return on investment (ROI) represents the ratio of net benefit against the initial investment. It is a measure of the profitability of the system. It is calculated using the formula,

$$ROI = \frac{B_n}{I_t} \quad (3)$$

where  $B_n$  is the net benefit and  $I_t$  is the total initial investment.

### 3. RESULTS AND DISCUSSION

PVsyst simulation results of the designed system based on the monthly metrological data of Owerri, Nigeria as sourced from the NASA-SSE database (shown in Table 2) are presented in this section.

#### 3.1 Orientation Optimization Result

A presentation of the orientation optimization test results is made in Table 6. A glance at the table easily reveals that the points that maximize the loss with respect to optimum, transposition factor, and global irradiation on the collector plane are azimuth  $180^\circ$  at plane tilts  $15^\circ$  and  $20^\circ$ . This means that any plane tilt between  $15^\circ$  and  $20^\circ$  at azimuth  $180^\circ$  is good for the project site. It was from this that the plane tilt  $20^\circ$  at azimuth  $180^\circ$  was selected for the project. Figures 5 and 6 show the PV Syst orientation optimization guide at plane tilt/azimuth  $20^\circ/180^\circ$  and the horizon line drawing at fixed plane tilt/azimuth  $20^\circ/180^\circ$ , respectively.

Table 6. Results of the orientation optimization test

S/N	Azimuth (degree)	Plane tilt (degree)	Transposition factor	Loss with respect to optimum	Global irradiation on collector plane (kWh/m <sup>2</sup> )
1	0	0	1.00	0.0%	783
2	0	5	0.98	-1.6%	770
3	0	10	0.96	-3.7%	753
4	0	15	0.94	-6.5%	732
5	0	20	0.90	-9.7%	707
6	0	25	0.87	-13.5%	677
7	0	30	0.82	-17.7%	645
8	0	35	0.78	-22.2%	609
9	0	40	0.73	-27.1%	571
10	0	45	0.68	-32.4%	529
11	180	0	1.00	0.0%	783
12	180	5	1.02	0.0%	797
13	180	10	1.03	0.0%	806
14	180	15	1.04	0.0%	811
15	180	20	1.04	0.0%	811
16	180	25	1.03	0.0%	806
17	180	30	1.02	0.0%	796
18	180	35	1.00	-0.1%	782
19	180	40	0.97	-2.5%	763
20	180	45	0.95	-5.5%	740

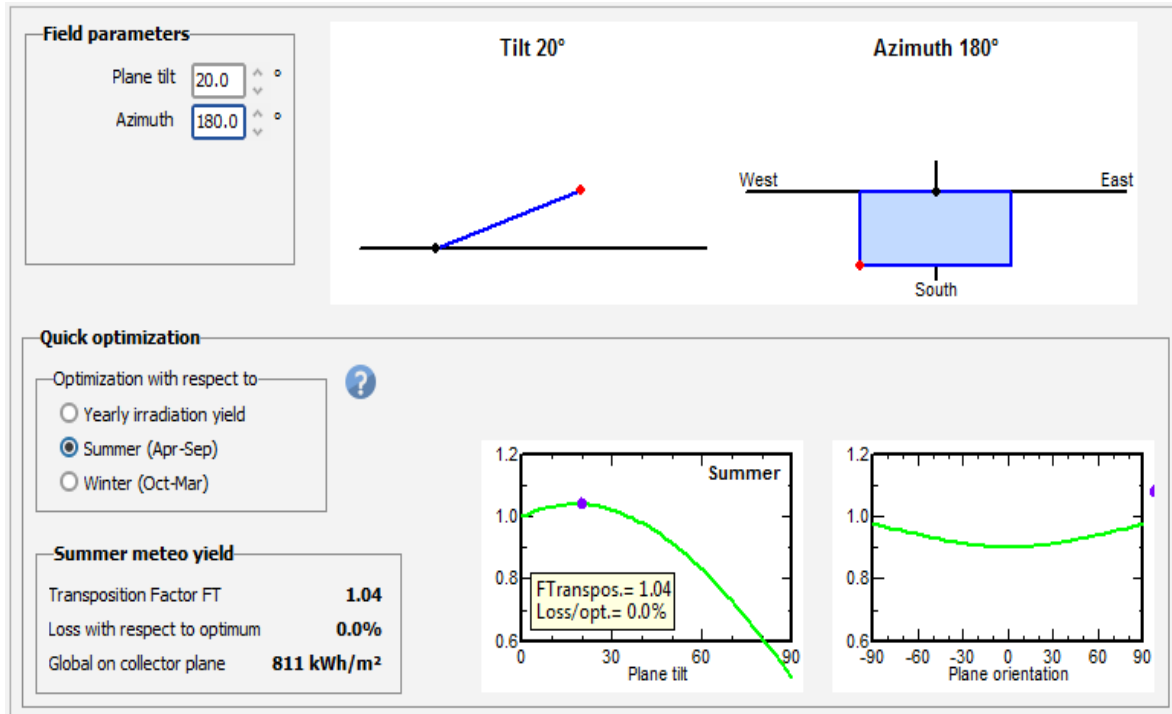


Fig. 5. Orientation optimization guide at plane tilt/azimuth 20°/180°

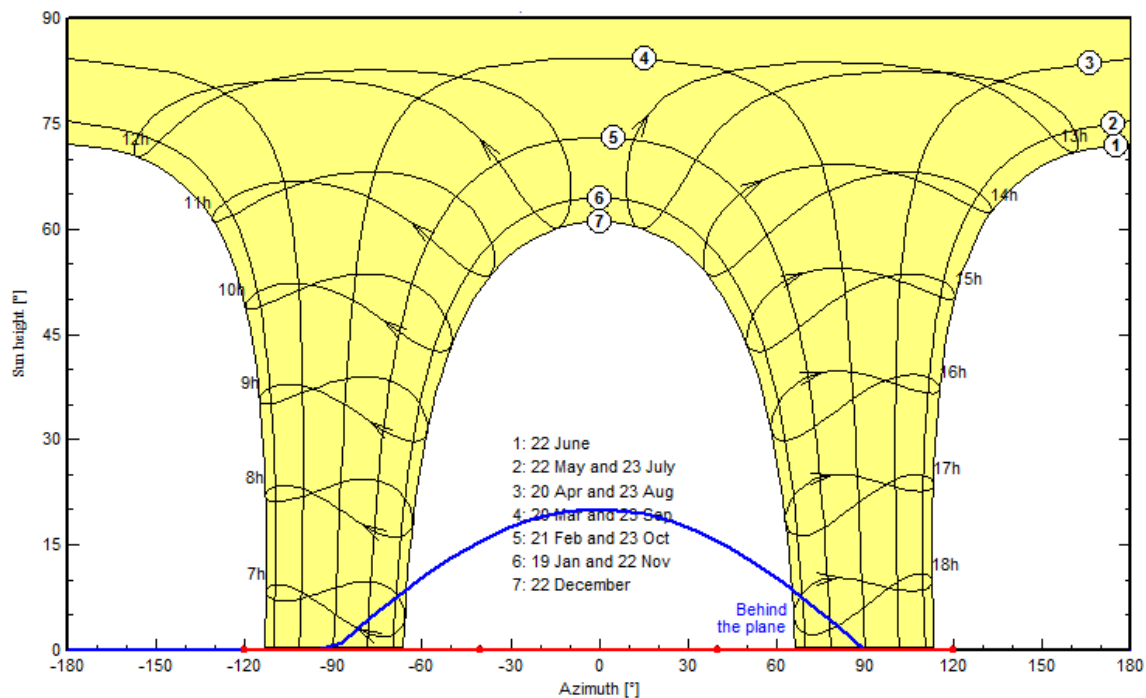


Fig. 6. Horizon line drawing at fixed plane tilt/azimuth 20°/180°

### 3.2 System Production and Losses

The Reference Incidence 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, Daily Array Output Energy, and Array Power Distribution charts are presented in Figures 7, 8, 9, 10, 11, 12, and 13, respectively.

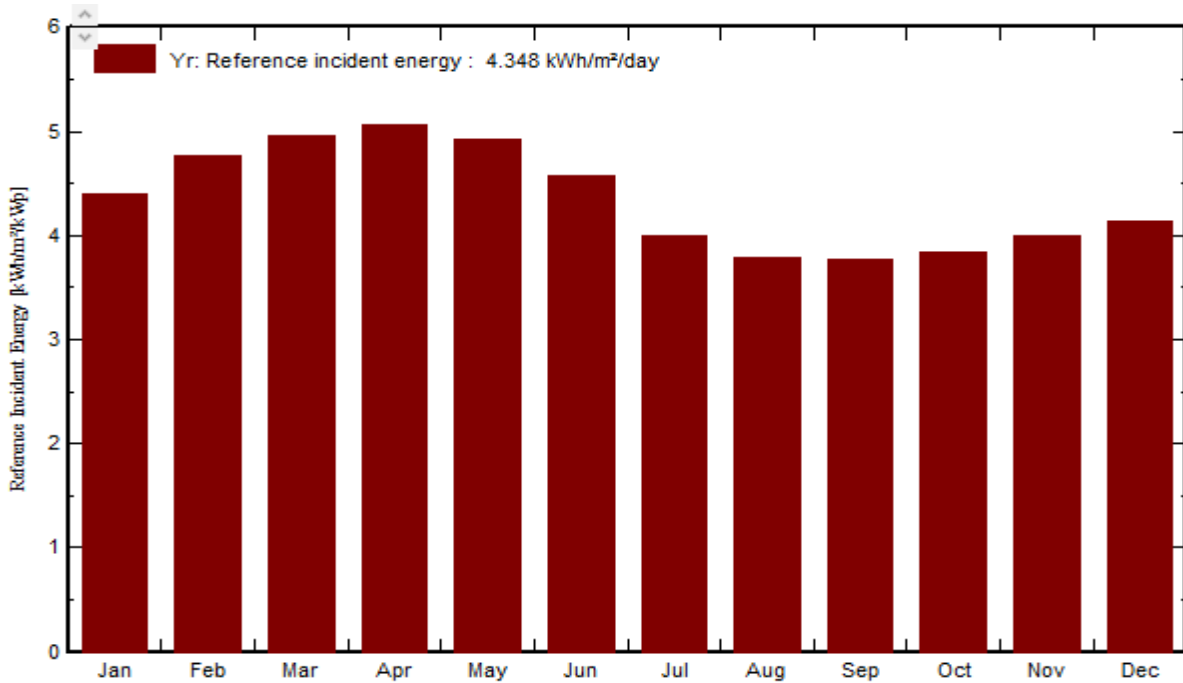


Fig. 7. Reference Incidence Energy in Collector Plane, Yr

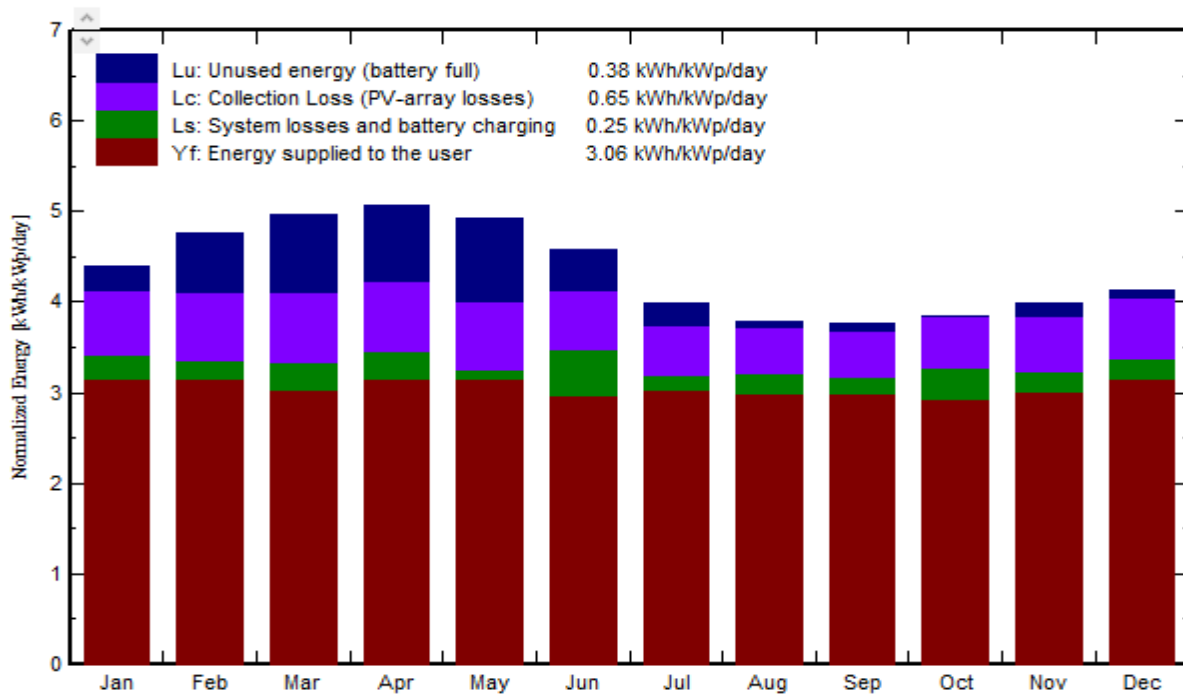


Fig. 8. Normalized Production (per installed kWp): Nominal power 468 kWp

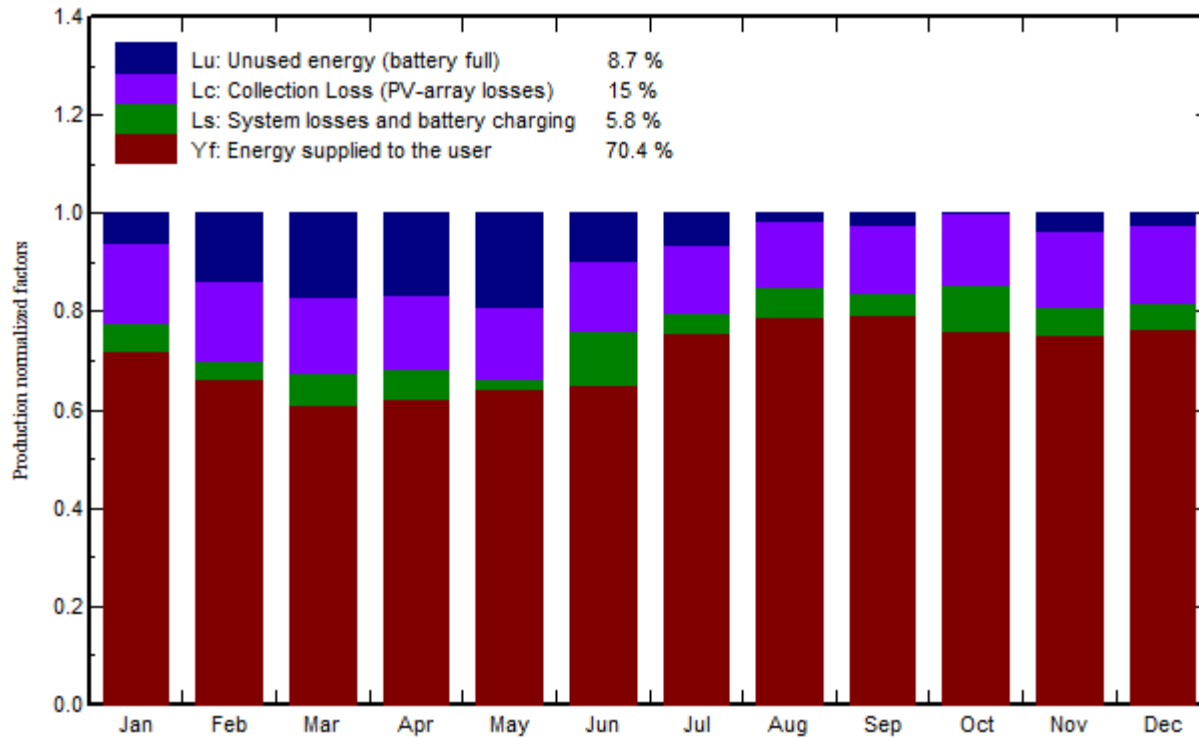


Fig. 9. Normalized Production and Loss Factors: Nominal power 468 kWp

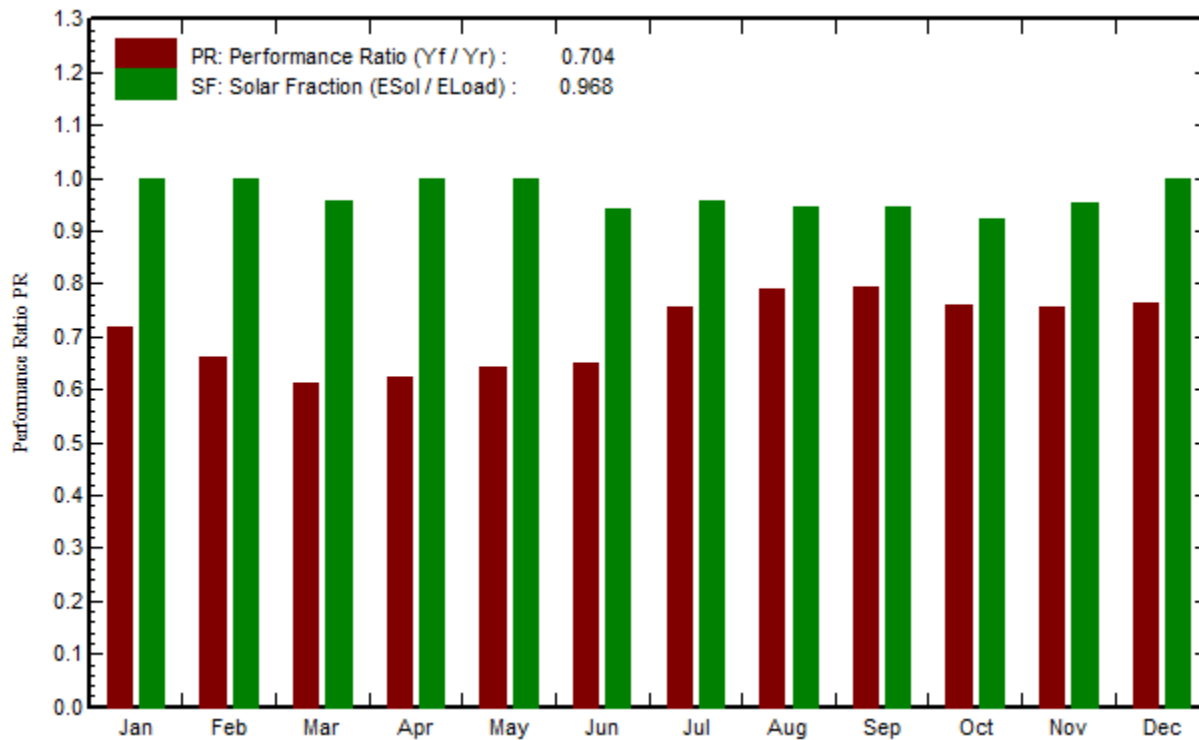


Fig. 10. Performance Ratio, PR and Solar Fraction, SF

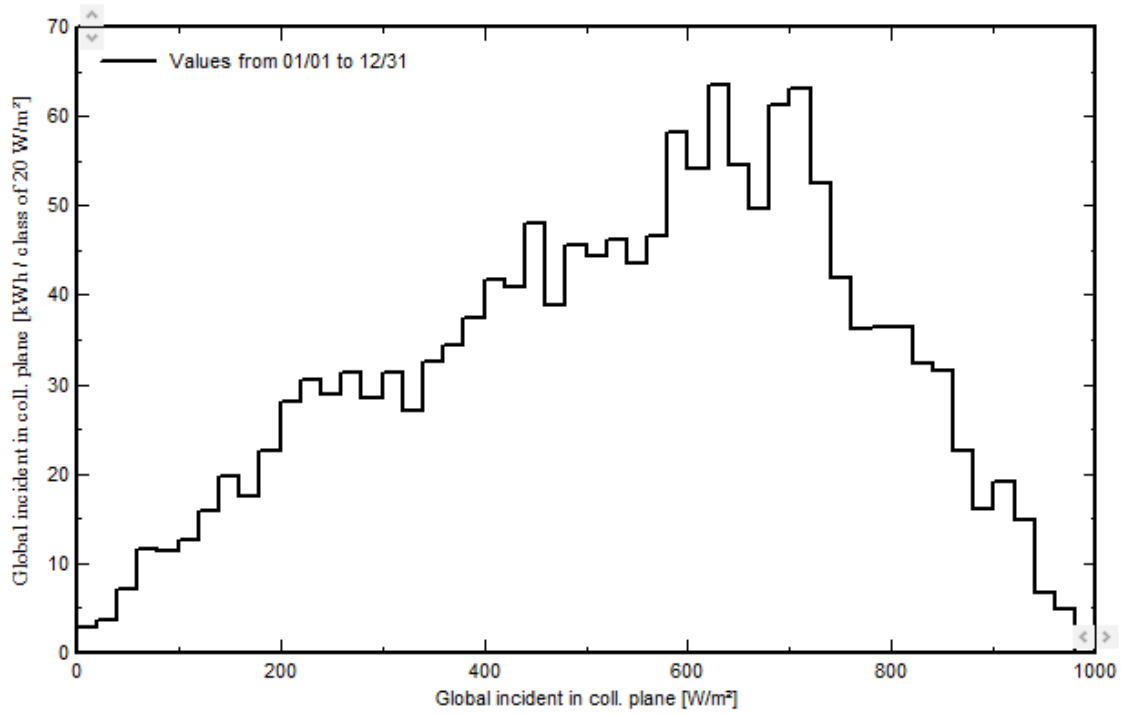


Fig. 11. Incidence Irradiation Distribution

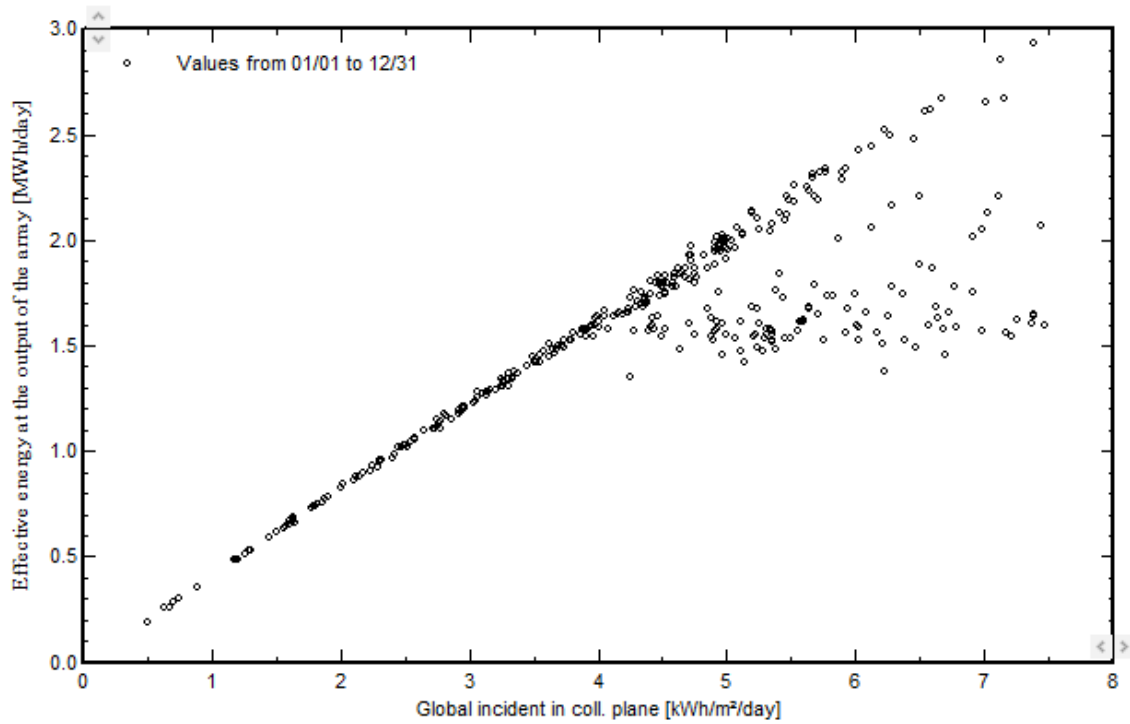
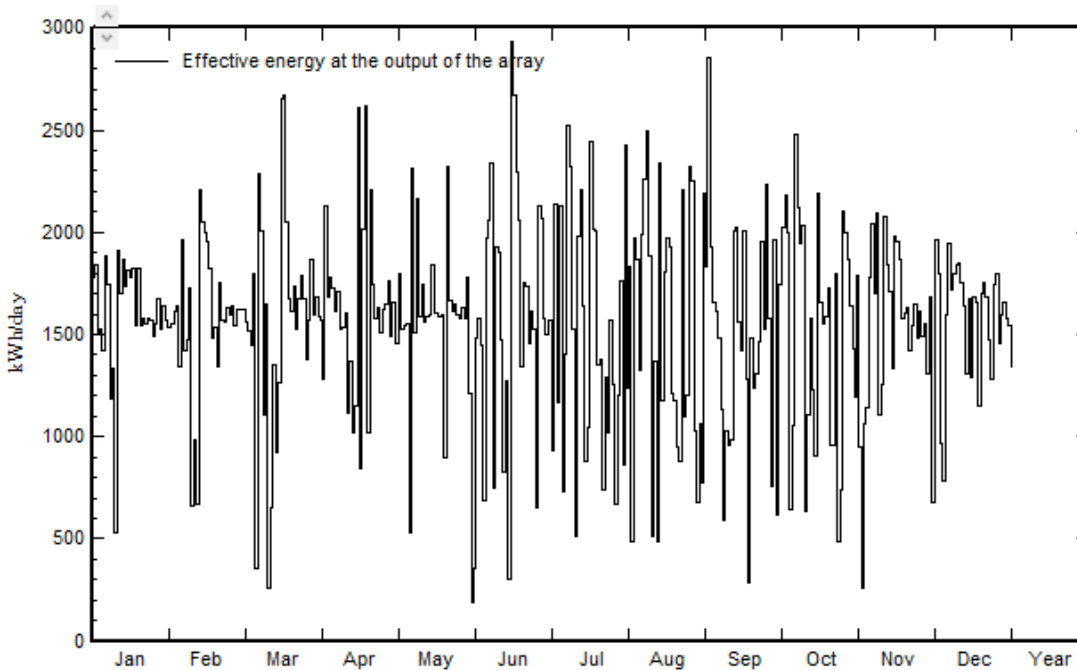


Fig. 12. Daily Input Output Diagram



**Fig. 13. Daily Array Output Energy**

From Figures 7, 8, and 9, it can be seen that the average reference incident energy in the collector plane is  $4.348 \text{ kWh/m}^2/\text{day}$ . With this incidence energy,  $1 \text{ kWp}$  of the PV array will supply  $3.06 \text{ kWh/day}$  (70.4%) of energy to the user. Battery charging and the system energy losses will account for the remaining 29.6% of energy. The distribution of this balance of energy is as follows: battery charging and system losses take  $0.25 \text{ kWh/kWp/day}$  (5.8%), PV array collection loss takes  $0.65 \text{ kWh/kWp/day}$  (15%), and the unused energy due to battery full accounts for the remaining  $0.38 \text{ kWh/kWp/day}$  (8.7%). From Fig. 10, the performance ratio, PR which is the ratio of energy delivered to the user,  $Y_f$  to the reference incident energy,  $Y_r$  (that is,  $Y_f/Y_r$ ) was realized as 0.704 (70.4%), while the solar fraction, SF which is the ratio of the energy delivered by the solar array,  $E_{Sol}$  to the user's energy needs,  $E_{Load}$  (that is  $E_{Sol}/E_{Load}$ ) was determined as 0.968 (96.8%). Fig. 11 which shows the incidence irradiation distribution was obtained by plotting the global incident energy in the collector plane (in kWh per class of  $20 \text{ W/m}^2$ ) against the global incidence energy in the collector plane (in  $\text{W/m}^2$ ). From Fig 12, it is observed that the effective energy variation at the array's output (in MWh/day) as against the global incident energy in the collector plane (in  $\text{kWh/m}^2/\text{day}$ ) is linear at lower values of the incident energy but the linearity disappears from about  $4.0 \text{ kWh/m}^2/\text{day}$  which is likely a result of the effects of higher PV array temperatures. Looking at Fig. 13, one can easily observe that the highest peaks of the effective energy at the PV array's output occur during the rainy season months of March to September which is ordinarily the months with the lowest global irradiation in Owerri, Nigeria (see Table 2). This is a result of the orientation optimization done using the rainy season months. The optimization helped to reduce the array losses that would have occurred in the dry season months with higher irradiation while boosting the energy production during the rainy season months with lower irradiation. This led to an increase in the efficiency of the system. This trend is also observed in Figures 7 and 10. The state of charge daily distribution and the system loss diagram of the batteries are shown in Figures 14 and 15, respectively.

To further elucidate the results of the technical simulation, the energy balances and main results are summarized in Table 7 while the production and technical performance indices of the system are summarized in Table 8.

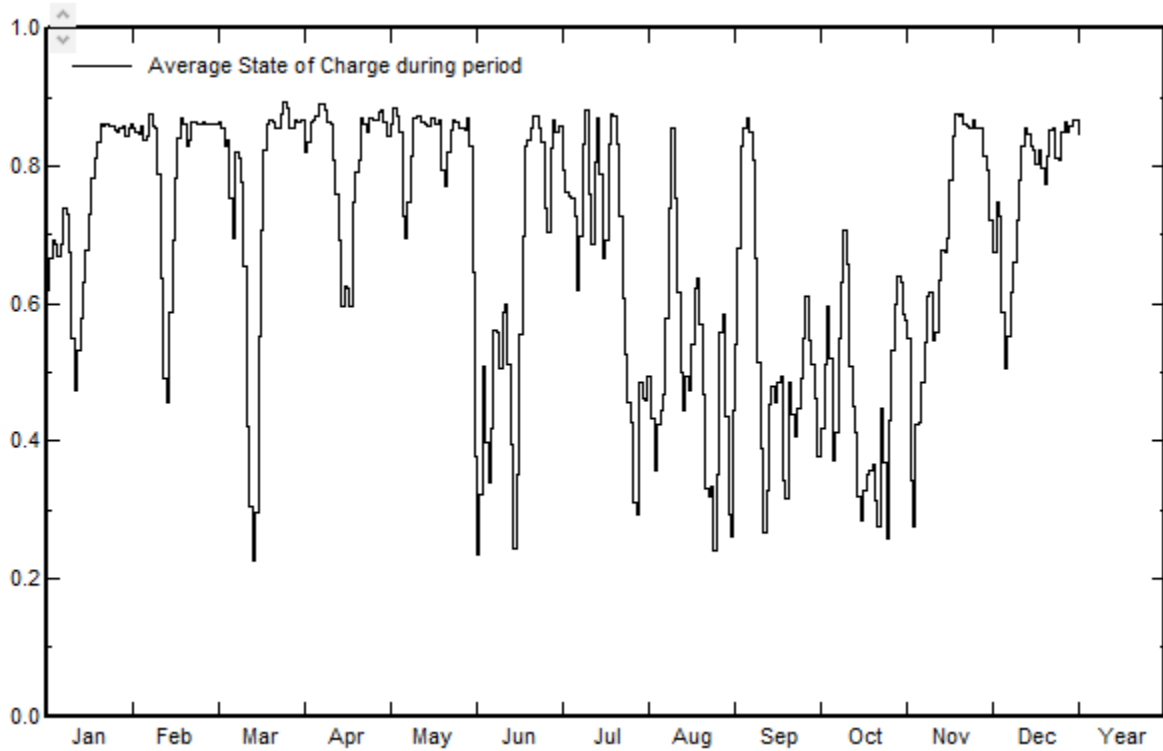


Fig. 14. Daily Distribution of the State of Charge

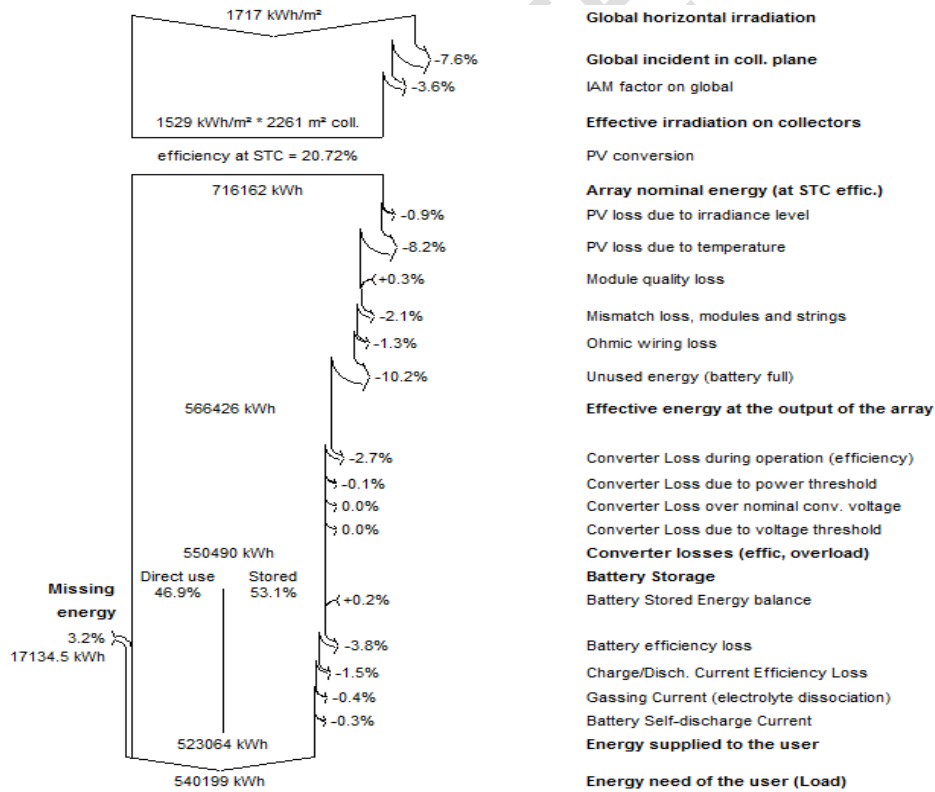


Fig. 15. Loss Diagram of the System

**Table 7. Energy balances and main results**

	<b>GlobHor (kWh/m<sup>2</sup>)</b>	<b>GlobEff (kWh/m<sup>2</sup>)</b>	<b>E_Avail (kWh)</b>	<b>EUnused (kWh)</b>	<b>E_Miss (kWh)</b>	<b>E_User (kWh)</b>	<b>E_Load (kWh)</b>	<b>SolFrac (ratio)</b>
January	171.4	128.8	52099	3785	0	45880	45880	1.000
February	156.5	127.9	51270	8538	0	41440	41440	1.000
March	164.9	148.8	59346	12196	1966	43914	45880	0.957
April	152.7	147.9	59127	11645	0	44400	44400	1.000
May	146.3	149.2	59462	13470	0	45880	45880	1.000
June	129.3	133.7	53584	6092	2670	41730	44400	0.940
July	119.4	120.5	48605	3682	1994	43886	45880	0.957
August	116.9	113.7	45918	694	2517	43363	45880	0.945
September	118.2	109.6	44401	1246	2406	41994	44400	0.946
October	132.4	114.4	46191	2	3520	42360	45880	0.923
November	145.2	114.0	46071	1991	2062	42338	44400	0.954
December	164.0	120.8	49093	1338	0	45880	45880	1.000
Year	1717.2	1529.2	615168	64678	17134	523064	540199	0.968

GlobHor = Global horizontal irradiation, GlobEff= Effective Global irradiation on collector plane for IAM and shadings, E\_Avail = Available Solar Energy, EUnused = Unused energy (battery full), E\_Miss= Missing energy, E\_User = Energy supplied to the user, E\_Load = Energy need of the user (Load), SolFrac = Solar fraction (E\_User/E\_Load)

**Table 8. Summary of system production and technical performance indices**

<b>System Production</b>	<b>Loss of Load</b>	<b>Battery Aging (State of Wear, SOW)</b>
Available Energy = 615,168 kWh/year	Time Fraction = 3.1%	Cycles SOW = 94.1%
Used Energy = 523,064 kWh/year	Missing Energy = 17,134 kWh/year	Static SOW = 90.0%
Excess (Unused) Energy = 64,678 kWh/year		Battery lifetime = 10.0 years
Performance Ratio, PR = 70.43%		
Solar Fraction = 96.83%		

With a 70.43% performance ratio and 3.1% loss of load time fraction, the system will be highly efficient and reliable as it will underperform only 3.1% of the time. The month with the highest missing energy is October while five months which include January, February, April, May, and December, have no missing energy.

### 3.3 Economic Evaluation Results

Results of the economic evaluation with no loan, 50% loan, and 80% loan financing are presented in Figures 16, 17, 18, and 19, while a summary of the important **economic performance indices** of the system is presented in Table 9.

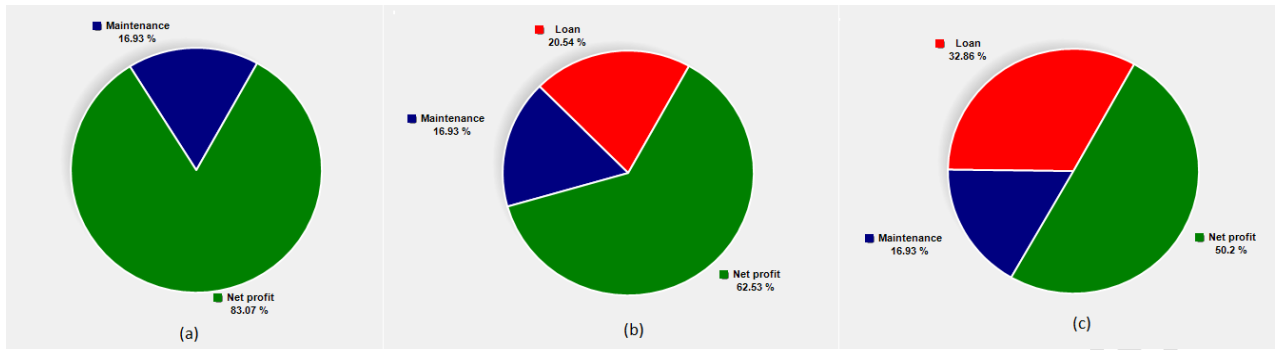


Fig. 16. Income allocation for (a) 0% loan, (b) 50% loan, and (c) 80% loan financing

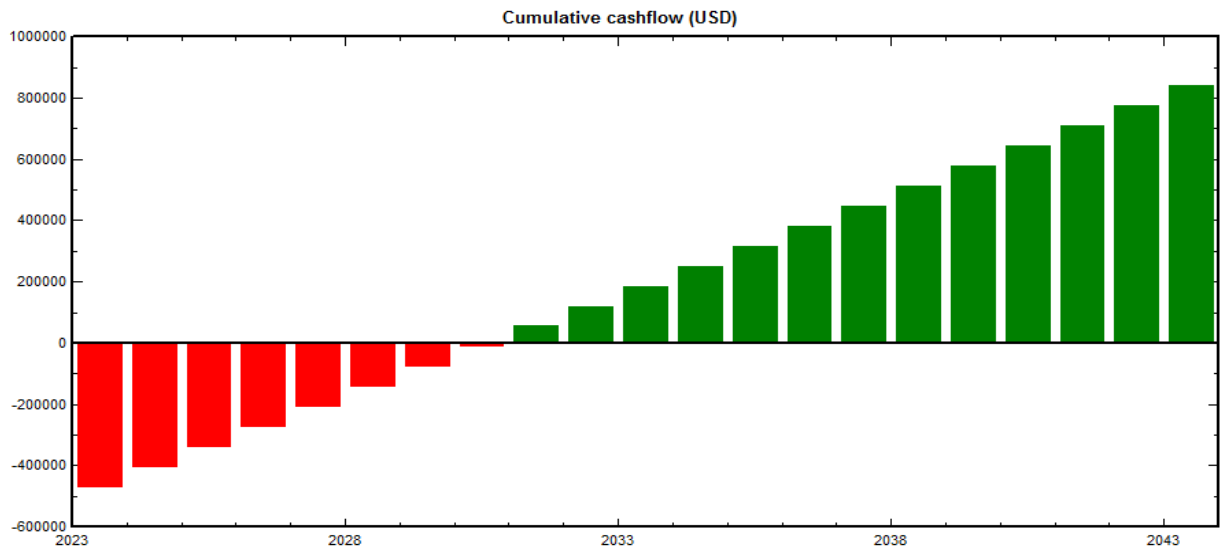


Fig. 17. Cumulative cash flow for the 0% loan financing case

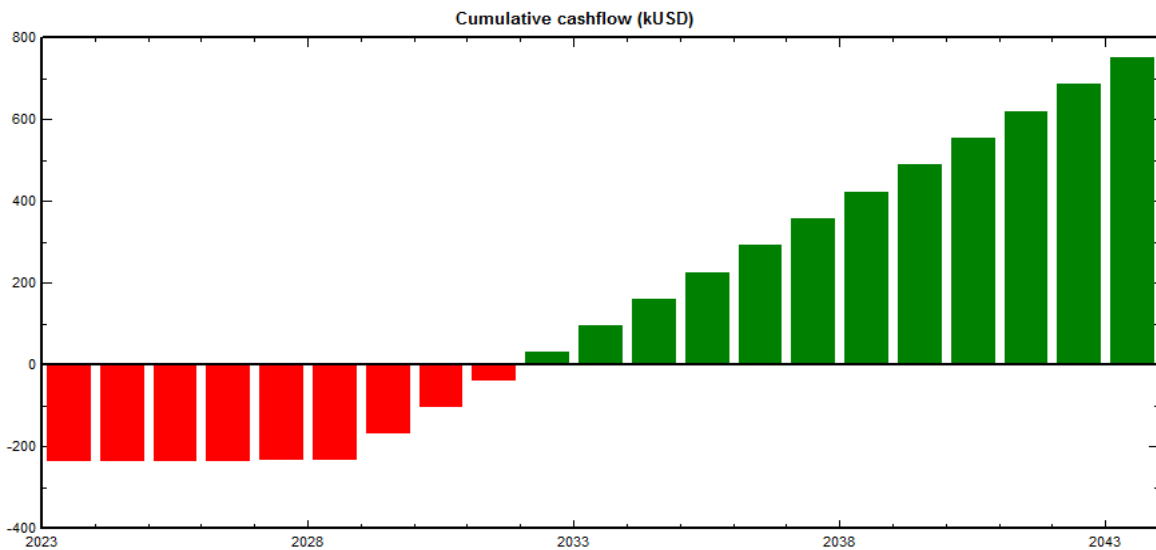


Fig. 18. Cumulative cash flow for the 50% loan financing case

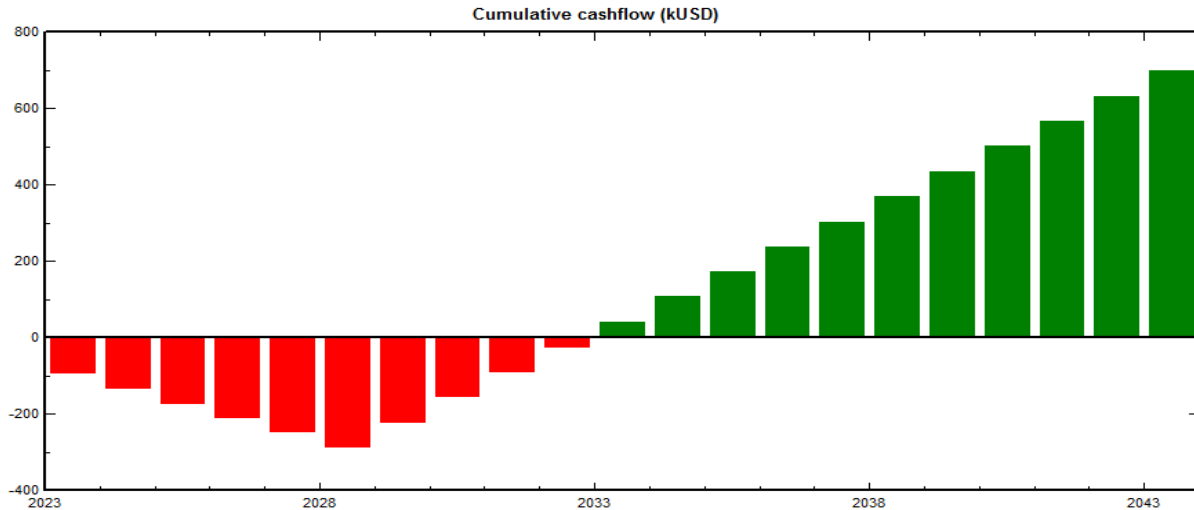


Fig. 19. Cumulative cash flow for the 80% loan financing case

Table 9. Summary of the economic evaluation results

<b>Evaluation with 0% Loan Financing</b>	<b>Evaluation with 50% Loan Financing</b>	<b>Evaluation with 80% Loan Financing</b>
<b><u>Installation cost financing</u></b> Own funds = 466,970.00 USD Loans = 0.00 USD Total = 466,970.00 USD	<b><u>Installation cost financing</u></b> Own funds = 233,485.00 USD Loans = 233,485.00 USD Total = 466,970.00 USD	<b><u>Installation cost financing</u></b> Own funds = 93,394.00 USD Loans = 373,576.00 USD Total = 466,970.00 USD
<b><u>Expenses</u></b> Operating cost (OPEX) = 13,350.00 USD/year Loan annuities = 0.00 USD/year Total yearly cost = 13,350.00 USD/year Levelized cost of energy = 0.0698 USD/kWh Specific cost = 1.00 USD/Wp	<b><u>Expenses</u></b> Operating cost (OPEX) = 13,350.00 USD/year Loan annuities for 5 yrs = 64,771.01 USD/year Total yearly cost = 29,542.75 USD/year Levelized cost of energy = 0.0784 USD/kWh Specific cost = 1.00 USD/Wp	<b><u>Expenses</u></b> Operating cost (OPEX) = 13,350.00 USD/year Loan annuities for 5 yrs = 103,633.62 USD/year Total yearly cost = 39,258.40 USD/year Levelized cost of energy = 0.0836 USD/kWh Specific cost = 1.00 USD/Wp
<b><u>Return on Investment</u></b> Energy tariff = 0.15 USD/kWh Net present value(NPV) = 842,699.16 USD Payback period = 7.2 years Return on Investment (ROI) = 180.5%	<b><u>Return on Investment</u></b> Energy tariff = 0.15 USD/kWh Net present value(NPV) = 752,329.11 USD Payback period = 8.5 years Return on Investment (ROI) = 161.1%	<b><u>Return on Investment</u></b> Energy tariff = 0.15 USD/kWh Net present value(NPV) = 698,107.07 USD Payback period = 9.4 years Return on Investment (ROI) = 149.5%

All the economic performance indices of the three financing considerations show that the project is highly feasible. The levelized cost of energy which is 0.0698 USD/kWh and 0.0784 USD/kWh for the 0% loan and 50% 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 produced energy is sold at this subsidized rate, the system will still be feasible.

#### 4. CONCLUSION

PVsyst 7.3 software was successfully used to design and simulate a standalone PV solar power plant for a typical 200 bungalow housing estate in Owerri, Nigeria. The design shows that with a global horizontal

irradiation of 4.70 kWh/m<sup>2</sup>/day reaching Owerri, Nigeria, a 468 kWp PV system is required to effectively supply the electricity needs of the estate with 1,480 kWh/day energy demand.

An electric energy totaling 615,168 kWh (approximately 615 MWh) will be produced by the PV system per year with a performance ratio of 70.4 % and a solar fraction of 96.8%.

The proposed project is highly feasible as the economic evaluation results show that the system installation cost is 466,970 USD at a specific cost of 1.0 USD/kWp, and the net present value (NPV) is positive at 842,699.16 USD, 752,219.11 USD, and 698,107.07 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 180.5%, 7.2 years, and 0.0698 USD/kWh, respectively for the 0% loan financing case; 161.1%, 8.5 years, and 0.0784 USD/kWh, respectively for the 50% loan financing case; and 149.5%, 9.4 years, and 0.0836 USD/kWh, respectively for the 80% loan financing case.

The designed PV system will still be feasible for the 0% and 50% loan financing cases even if the energy tariff is billed at the current subsidized electricity tariff rate in Nigeria which is about 0.08 USD/kWh. This is because the levelized cost of energy for the two cases, which is 0.0698 USD/kWh and 0.0784 USD/kWh, respectively, is lower than the subsidized 0.08 USD/kWh energy tariff.

Housing estate developers should, therefore, adopt solar energy as the source of electricity for the estates in Owerri and its environs as it is highly profitable in both returns on investment and carbon footprint savings.

## REFERENCES

1. Jung TY, Huh M, Moon J. Goal 7: affordable and clean energy. In: Sustainable Development Goals in the Republic of Korea. 1st Editio. Taylor & Francis; 2018. p. 65–84.
2. Song J, Lee EW. Goal 11: sustainable city and communities. In: Sustainable Development Goals in the Republic of Korea. 2018. p. 110–37.
3. BOI. The N6 Billion BOI Solar Energy Fund. Solar Energy. 2020. Accessed 15 July 2022. Available: <https://www.boi.ng/solar-energy/>
4. ADB. Sustainable Energy Fund For Africa. African Development Bank. 2022. Accessed 15 July 2022. Available: <https://www.afdb.org/en/topics-and-sectors/initiatives-partnerships/sustainable-energy-fund-for-africa>
5. REA. Standalone Solar Home Systems for Households and MSMEs Output Based Fund. Nigerian Electrification Project - Rural Electrification Agency. 2022. Accessed 15 July 2022. Available: <https://nep.rea.gov.ng/solar-home-systems/>
6. Agbo EP, Edet CO, Magu TO, Njok AO, Ekpo CM, Louis H. Solar energy: A panacea for the electricity generation crisis in Nigeria. *Heliyon*. 2021;7(5):1–21. <https://doi.org/10.1016/j.heliyon.2021.e07016>
7. Agbo EP, Ettah EB, Eno EE. The impacts of meteorological parameters on the seasonal, monthly, and annual variation of radio refractivity. *Indian J Phys*. 2021;95(2):195–207. <https://doi.org/10.1007/s12648-020-01711-9>
8. Abdullahi D, Suresh S, Renukappa S, Oloke D. Key Barriers to the Implementation of Solar Energy in Nigeria: A Critical Analysis. *IOP Conf Ser Earth Environ Sci*. 2017;83.
9. Chanchangi YN, Adu F, Ghosh A, Sundaram S, Mallick TK. Nigeria's energy review: Focusing on solar energy potential and penetration. *Environ Dev Sustain*. 2022;
10. Oghogho I, Sulaimon O, Egbune D, Abanihi K V. Solar Energy Potential and Its Development for

- Sustainable Energy Generation in Nigeria: a Road Map To Achieving This Feat. *Int Journals Eng Manag Sci.* 2014;5(2):61–7.
11. Oliveti G, Marletta L, Arcuri N, De Simone M, Bruno R, Evola G. Solar energy. *Green Energy and Technology.* Delft University of Technology; 2014. 159–214 p.
  12. Ohajianya AC, Abumere OE, Osarolube E. Design of 2.5 kW Photovoltaic System Accumulated Rain Water Hybrid Power Plant and Estimation of Energy Production Capability of the Rain Water Turbine. *Niger J Phys.* 2016;27(1):26–36. Available from: [www.njpng.org](http://www.njpng.org)
  13. Deambi S. *Photovoltaic System Design: Procedures, Tools and Applications.* Taylor & Francis. CRC Press; 2016.
  14. Lalwani M, Kothari DP, Singh M. Investigation of Solar Photovoltaic Simulation Softwares. *Int J Appl Eng Res.* 2010;1(3):585–601.
  15. Al-Zoubi H, Al-Khasawneh Y, Omar W. Design and feasibility study of an on-grid photovoltaic system for green electrification of hotels: a case study of Cedars hotel in Jordan. *Int J Energy Environ Eng.* 2021;12(4):611–26. <https://doi.org/10.1007/s40095-021-00406-z>
  16. Garg A, Ankita Bhatia M, Iqbal A, Deepika Chauhan D. Design of Solar PV System. *IRE Journals.* 2018;1(9):43–8.
  17. Kumar P, Deokar S. Designing and Simulation Tools of Renewable Energy Systems: Review Literature. *Adv Intell Syst Comput.* 2018;563(May):315–24.
  18. Bentouba S, Bourouis M, Zioui N, Pirashanthan A, Velauthapillai D. Performance assessment of a 20 MW photovoltaic power plant in a hot climate using real data and simulation tools. *Energy Reports.* 2021;7:7297–314. <https://doi.org/10.1016/j.egy.2021.10.082>
  19. Komrit S. *Comparative Analyses of Solar Photovoltaic, Wind, and Hybrid Energy Systems: Case Study of Thailand.* California State University, Sacramento; 2020.
  20. Kumi EN, Brew-Hammond A. Design and Analysis of a 1MW Grid-Connected Solar PV System in Ghana. *African Technol Policy Stud Netw Work Pap Ser.* 2013;(78):1–24.
  21. Faiz FUH, Shakoor R, Raheem A, Umer F, Rasheed N, Farhan M. Modeling and Analysis of 3 MW Solar Photovoltaic Plant Using PVSyst at Islamia University of Bahawalpur, Pakistan. *Int J Photoenergy.* 2021;2021.
  22. Iqbal A, Iqbal MT. Design and analysis of a stand-alone PV system for a rural house in Pakistan. *Int J Photoenergy.* 2019;2019.
  23. Jagadale P, Choudhari A, Jadhav S. Design and Simulation of Grid Connected Solar Si-Poly Photovoltaic Plant Using PVSyst For Pune, India Location. *Renew Energy Res Appl.* 2022;3(1):41–9.
  24. Navothna B, Thotakura S. Analysis on Large-Scale Solar PV Plant Energy Performance–Loss–Degradation in Coastal Climates of India. *Front Energy Res.* 2022;10(April):1–9.
  25. Lee-Jones D. *Feasibility Study of Building Integrated Hybrid Solar Pv and Wind Power Systems: a Case-Study on the Swedish Island of Gotland.* Uppsala University; 2016.
  26. Nguyen TB, Van PH. Design, Simulation, and Economic Analysis of A Rooftop Solar PV System in Vietnam. *EAI Endorsed Trans Energy Web.* 2021;8(35):1–12.
  27. Tarigan E, Djuwari, Kartikasari FD. Techno-economic Simulation of a Grid-connected PV System Design as Specifically Applied to Residential in Surabaya, Indonesia. *Energy Procedia.* 2015;65:90–9. <http://dx.doi.org/10.1016/j.egypro.2015.01.038>
  28. Windarta J, Saptadi S, Denis, Satrio DA, Silaen JS. Technical and economical feasibility analysis on household-scale rooftop solar power plant design with on-grid system in Semarang city. *Edelweiss Appl Sci Technol.* 2021;5(1):14–20.
  29. Ani VA, Ani EO. Simulation of Solar-Photovoltaic Hybrid Power Generation System with Energy

Storage and Supervisory Control for Base Transceiver Station (BTS) Site Located in Rural Nigeria. *Int J Renew Energy Res.* 2014;4(1):23–30.

30. Njoku C, Onojo JO, Chukwuchekwa N, Okafor KC. Design and Simulation of a Hybrid Biomass-Solar Renewable Energy System. *World J Eng Res Technol.* 2018;4(August):368–78.
31. Ohajianya AC. Simulation and Analysis of a Standalone PV Solar Power Plant for a Housing Estate in Abuja, Nigeria. *Int J Renew Energy Res.* 2023;13(3):1233–46. <https://doi.org/10.20508/ijrer.v13i3.14148.g8796>
32. Ohajianya AC, Abumere OE, Osarolube E. Design, Construction and Testing of a 160 W Model of Photovoltaic System-Accumulated Rain Water Hybrid Power Plant. *Niger J Phys.* 2016;27(1):12–21.

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