Original Research Article

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. The 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 expose 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 technical and economic feasibility using PVsyst 7.3 software. The design showed that with a global horizontal irradiation of 4.70 kWh/m^2/day reaching Owerri, Nigeria, a 468 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 615,168 kWh of electric energy 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'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 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.

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].

Lack of awareness of the benefits of installing and using solar energy systems was identified as one of the key barriers to the implementation of solar energy systems in Nigeria [8]. Technical issues like early components failure due to poor design and lack of maintenance, and their discouraging effect on prospective new users are other limiting factors to PV solar systems penetration in Nigeria. This is due to inadequate human capacity building and related training in solar energy development, installation, and maintenance in the country [9]. Other challenges include poverty which made it impossible for a majority of the masses to afford the high initial cost of installing a PV system, and fear of theft and vandalism due to the high level of insecurity in the country [9]. To tackle these issues and create a favorable condition for the widespread deployment of 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 tackling the 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]. The block diagram of a standalone PV solar power plant is shown in Fig. 2.

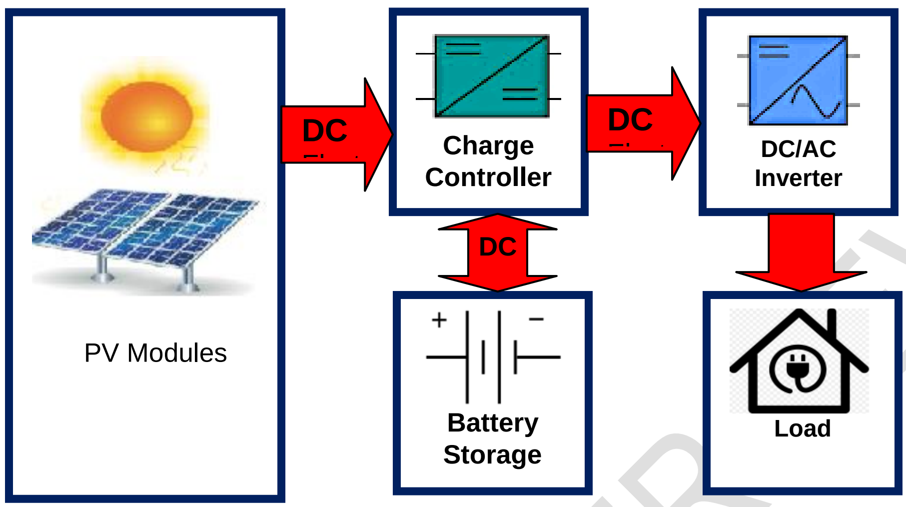

Fig. 2. Block diagram of a standalone PV solar power plant

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 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. There are also softwares that can be used to design and/or simulate the performance of solar PV systems. For the simulation softwares that do not incorporate design features, the designer will have to manually estimate the components' sizes using the design formulas before using the softwares to simulate the performance of the designed system. The solar PV power plant design formulas and components sizing procedure have been presented in our earlier publication [12].

1.3 Solar PV Systems Design and Simulation Softwares

Some of the softwares that can be employed in the design and/or simulation of solar PV systems include RETScreen, PV F-Chart, SolarDesign Tool, INSEL, TRNSYS, Solar Advisor Model (SAM), PVsyst, SolarPro, PV-DesignPro-G, and HOMER [13]. PV software simulators on the market have different advantages and limitations based on the specific areas of interest of the developers [14]. The four most popular of these softwares due to their features are RETScreen, PVSyst, SolarPro, and HOMER.

RETScreen is a decision-support software developed by the Government of Canada. It has the needed database [which is sourced from 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 need of a University in Ghana [20]. The results showed that with the 4.30kWh/m^2/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_2 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^2/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. Igbal [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 if 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_2 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^2/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_2, 3.46 kg of NOx, 1295 kg of CO_2, 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.

Performance and economic viability studies of PV systems have also been done 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 GovernmentArea of Enugu State, Nigeria. The HOMER simulation results show that with an annual average solar radiation of 4.92 kWh/m^2/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^2/day [30]. PV system was also found to be highly feasible in Abuja, Nigeria as a PVsyst simulation showed 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. With an energy tariff of 0.15 USD/kWh, 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 sourced from NASA and many other stations across the world. Another attractive feature of this software is its large components database which helps in the system design, economic evaluation, and payback period estimation.

2.1 PV System Design

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

Table 1. 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	Lamp1(LED)	10 W	10	100 W	10	1,000 Wh/d	200 kWh/d
2	Lamp2(LED)	5 W	04	20 W	10	200 Wh/d	40 kWh/d
3	TV/PC	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	Washing machine/ Blender	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
						Total	1,480 kWh/d

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 fixed at 0^0 and 180^0 while the plane tilt was varied from 0^0 to 45^0 for the two azimuths. The transposition factor, loss with respect to optimum, and global irradiation on collector plane were noted for each plane tilt. From this test, the best plane tilt and azimuth were selected as 20^0 and 180^0, respectively.

The daily energy demand data of the households 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 Meteo Data of Owerri, Nigeria from NASA-SSE Data Base

	Global horizontal irradiation (kWh/m^2/day)	Horizontal diffuse irradiation (kWh/m^2/day)	Temperature (^{0}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
Year	**4.70**	**2.08**	**24.9**

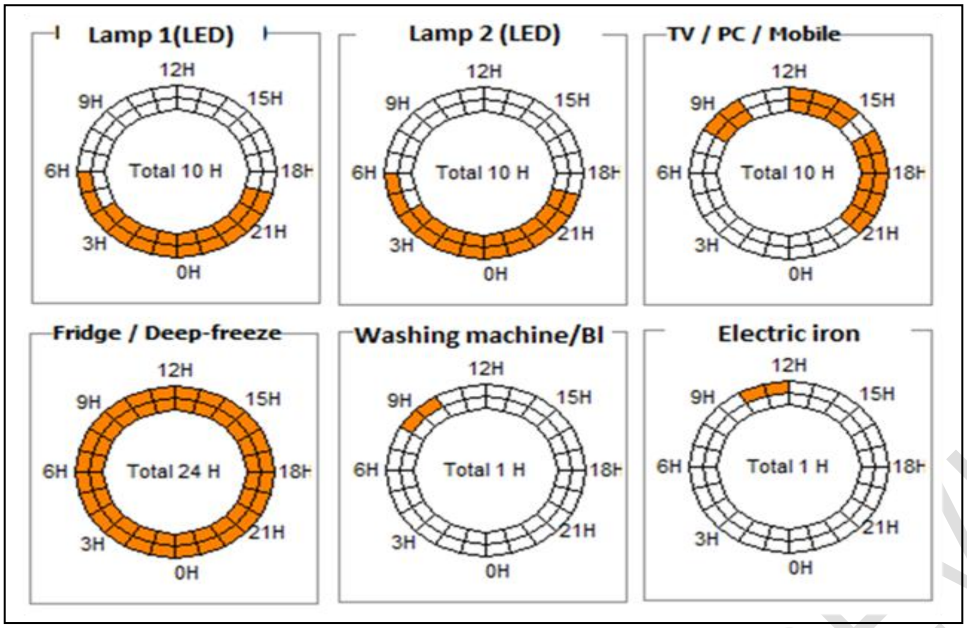

Fig. 3. The hourly distribution of energy demand

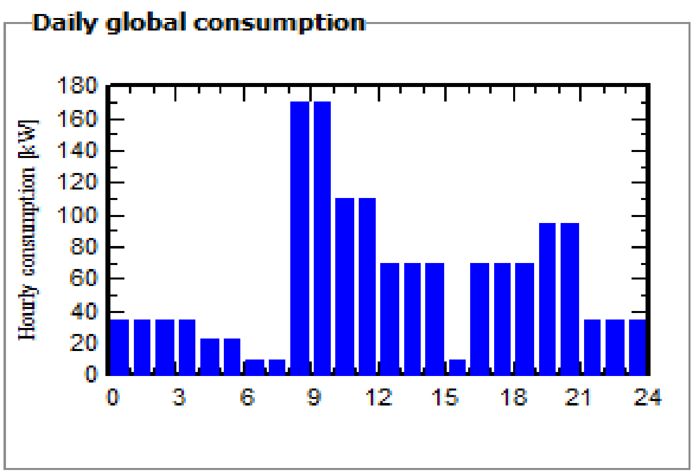

Fig. 4. Daily global consumption

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 software generated the required number and arrangement of batteries to meet the set conditions.

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

Table 3. The designed system components

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 financing, 50% loan financing, and 80% loan financing which 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
			Total	**466,970**

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
	Total	**13,350**	**20**	**267,000**

The levelized cost of energy and other important economic performance indices of the system which include the net present value, the payback period, and the return on investment, were determined. 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:

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

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 of time. It is calculated using the formula:

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

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. 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 thus:

$$ROI = \frac{Netbenefitatt\ \ heendoflifetime}{Totalinvestment} \quad (3)$$

3. RESULTS AND DISCUSSION

PVsyst simulation results of the designed system based on the Monthly Meteo Data of Owerri, Nigeria from NASA-SSE Data Base as already shown in Table 2 are presented in this section.

3.1 Orientation Optimization Result

The orientation optimization test results are presented in Table 6. A glance at this table easily reveals that the points that maximize the transposition factor, loss with respect to optimum, and global irradiation on collector plane are azimuth 180^0 at plane tilts 15^0 and 20^0. This means that any plane tilt between 15^0 and 20^0 at azimuth 180^0 is good for the project site. It was from this that the plane tilt 20^0 at azimuth 180^0 was selected for the project. The PV Syst orientation optimization guide at plane tilt/azimuth $20^0/180^0$ is shown in Fig. 5 while the horizon line drawing at fixed plane tilt/azimuth $20^0/180^0$ is shown in Fig. 6.

Table 6. Orientation optimization results

S/N	Azimuth (degree)	Plane tilt (degree)	Transposition factor	Loss with respect to optimum	Global irradiation on collector plane (kWh/m^2)
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

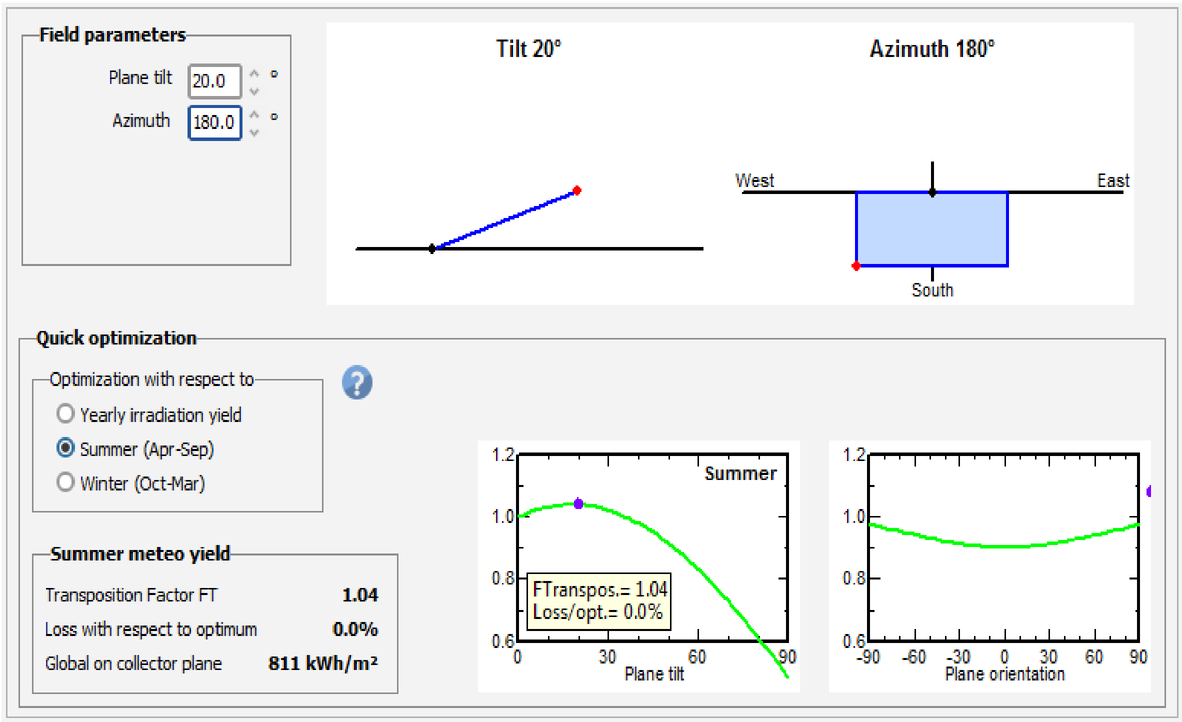

Fig. 5. Orientation optimization guide at plane tilt/azimuth $20^0/180^0$

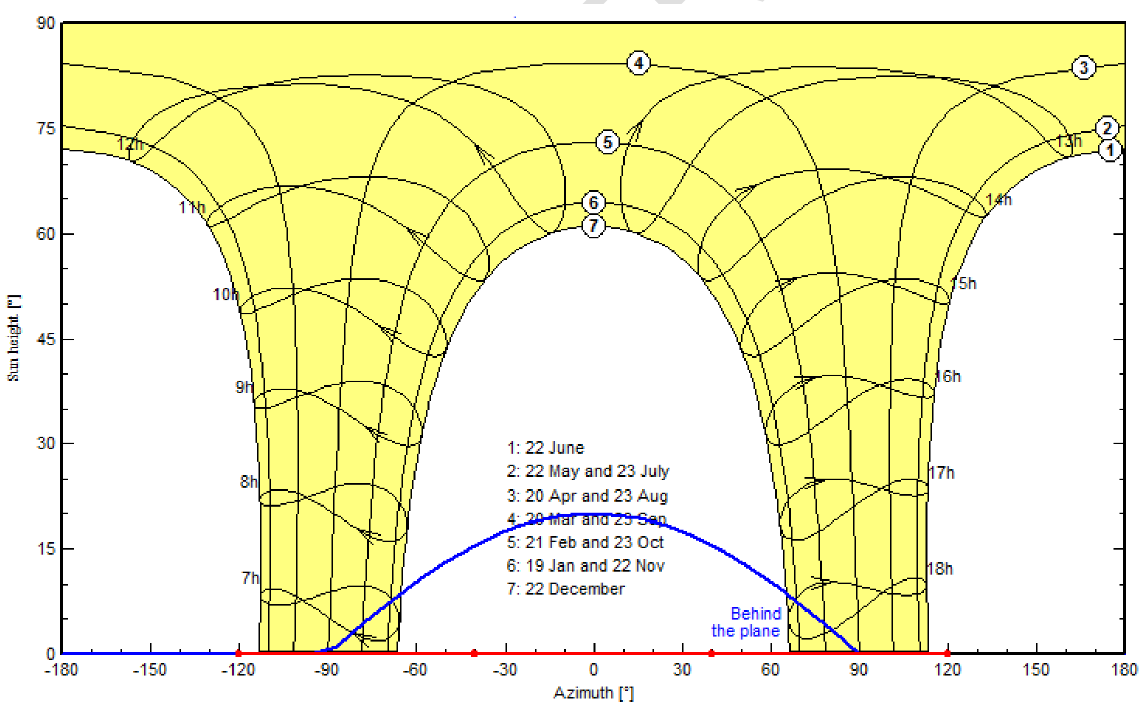

Fig. 6. Horizon line drawing at fixed plane tilt/azimuth $20^0/180^0$

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.

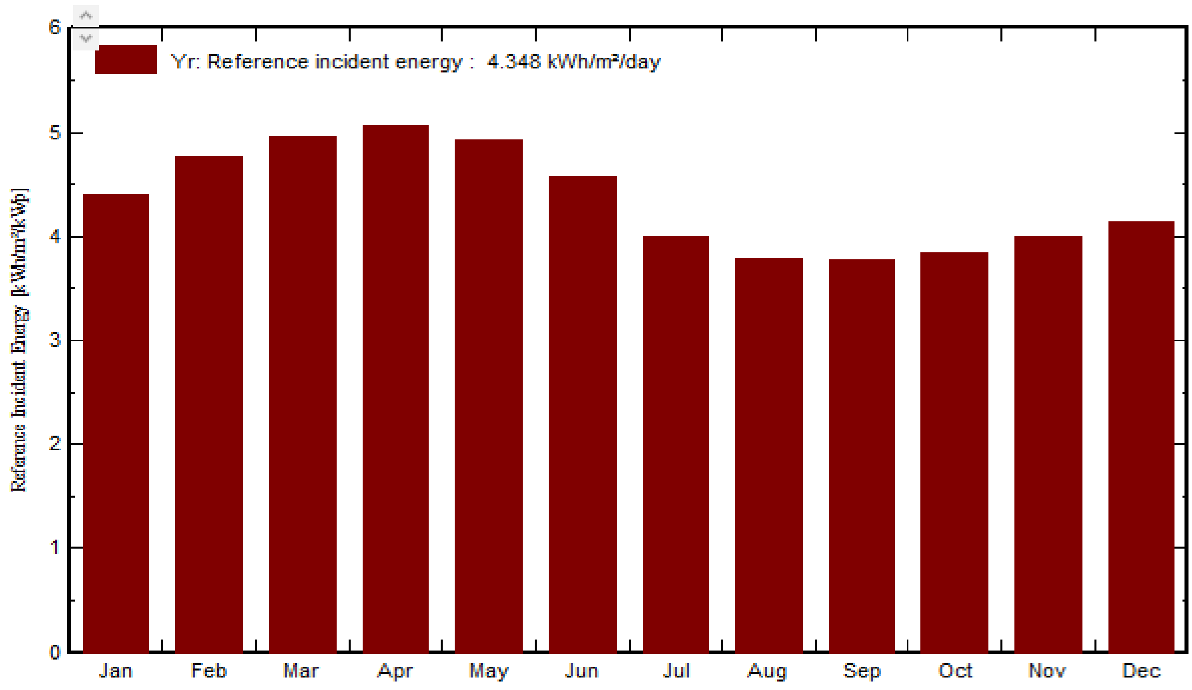

Fig. 7. Reference Incidence Energy in Collector Plane, Yr

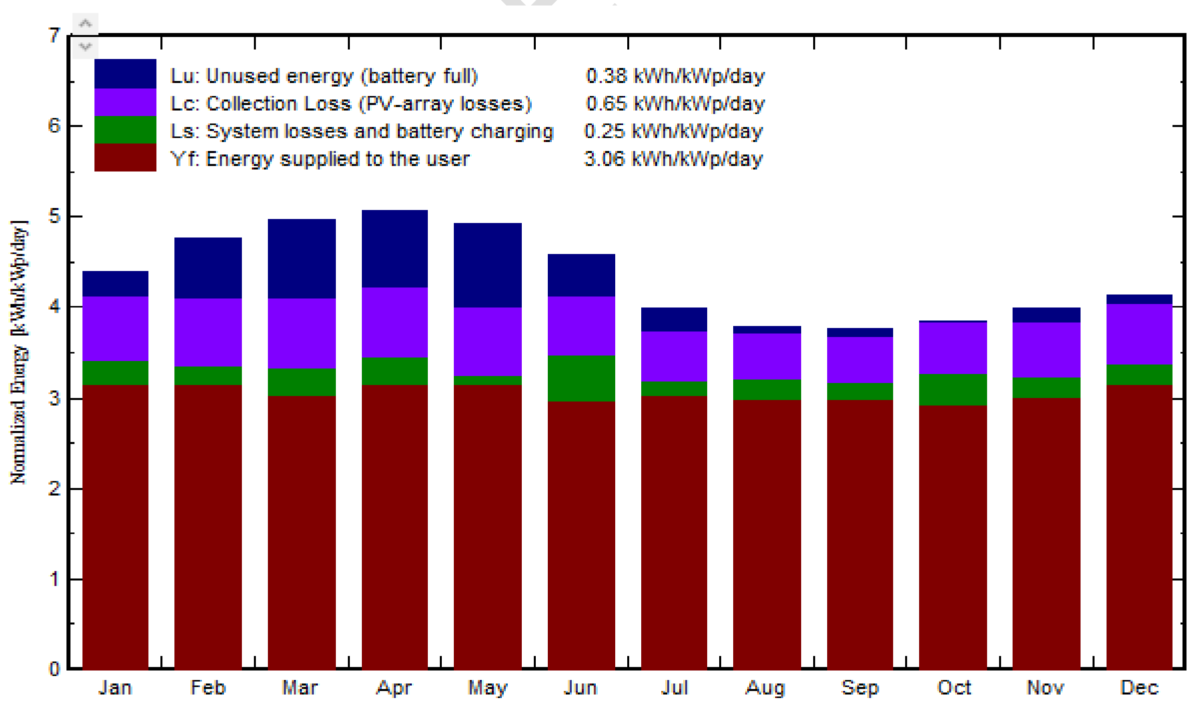

Fig. 8. Normalized Production (per installed kWp): Norminal power 468 kWp

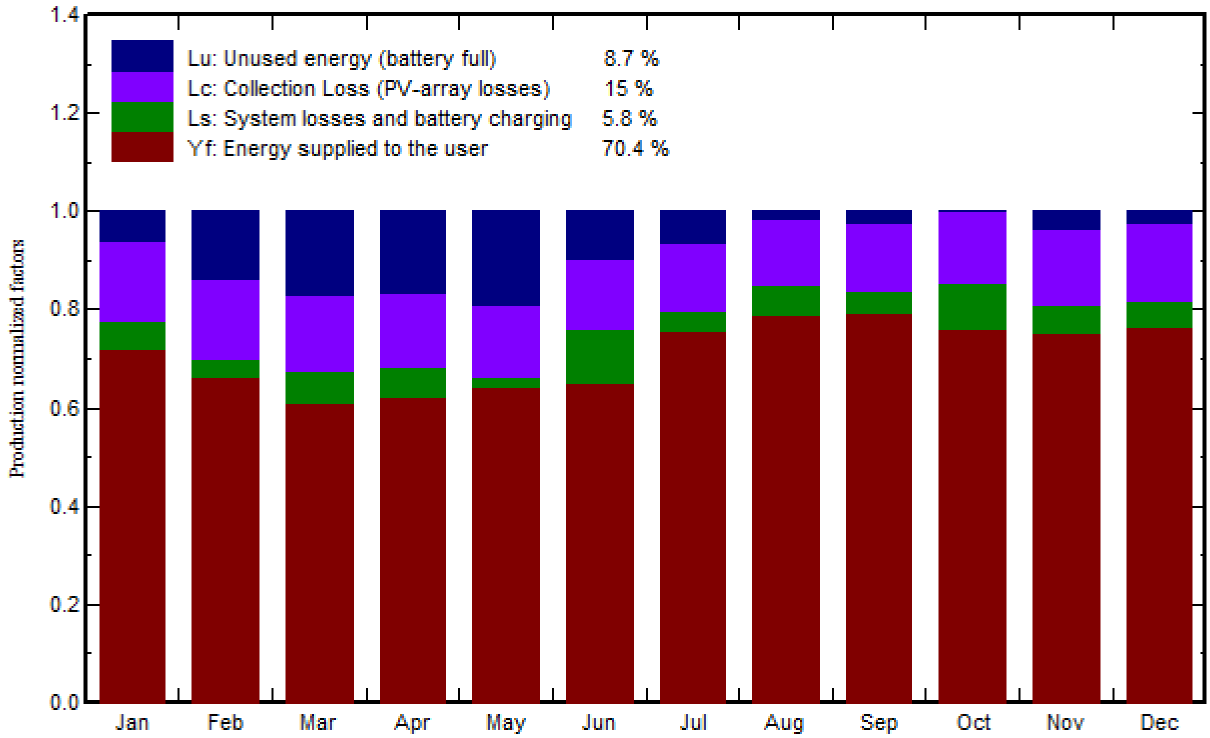

Fig. 9. Normalized Production and Loss Factors: Nominal power 468 kWp

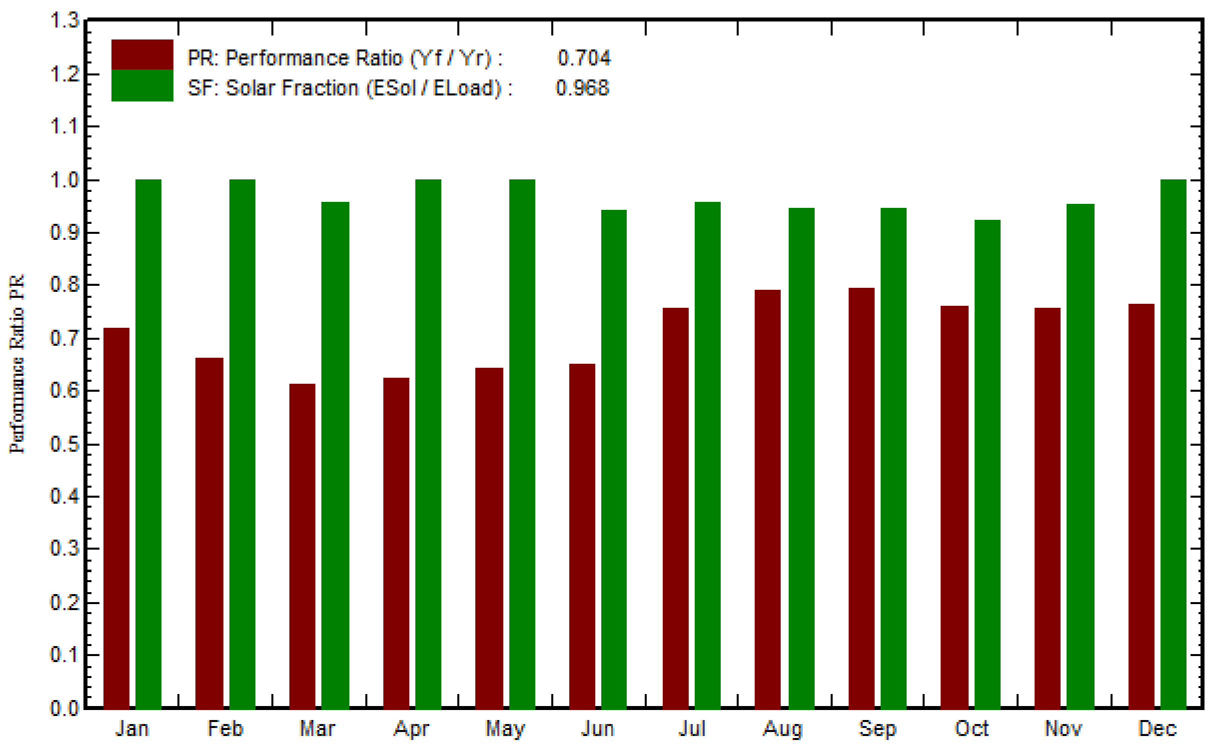

Fig. 10. Performance Ratio, PR and Solar Fraction, SF

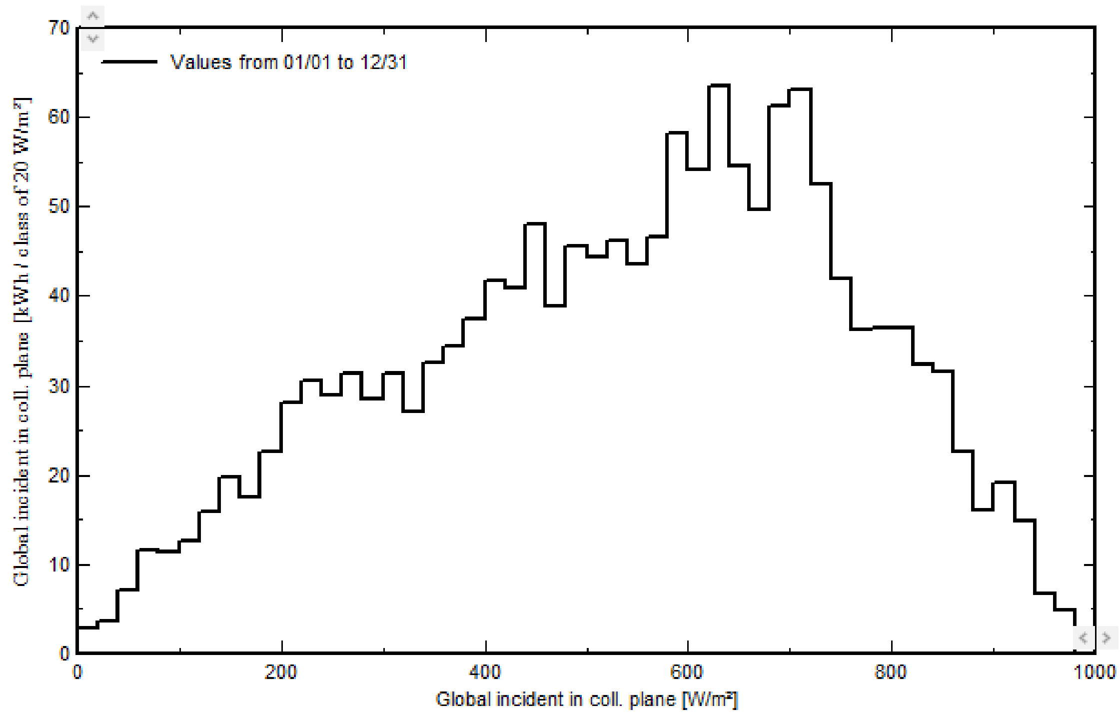

Fig. 11. Incidence Irradiation Distribution

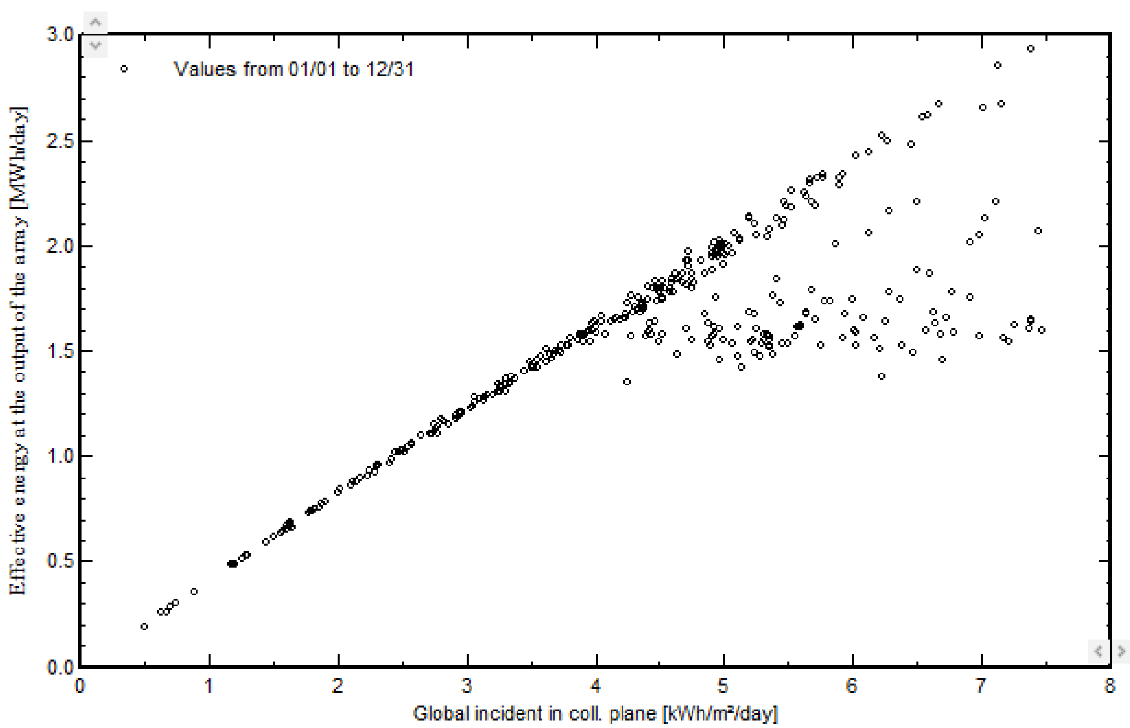

Fig. 12. Daily Input Output Diagram

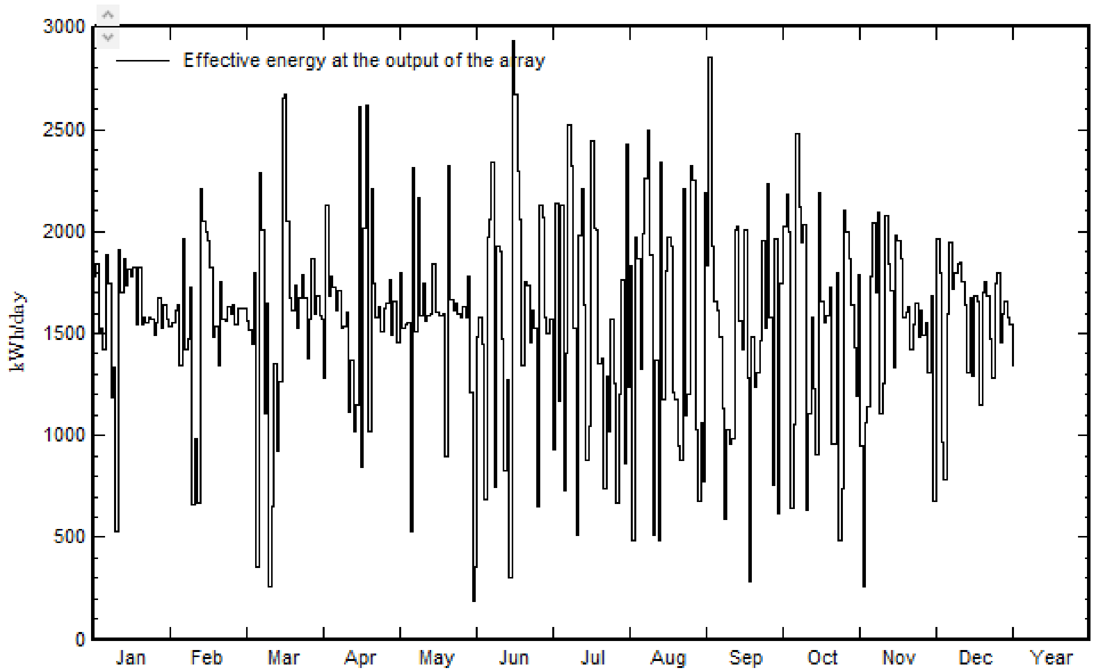

Fig. 13. Daily Array Output Energy

From Figures 7, 8, and 9, it can be seen that the average reference incident energy in the collector plane is 4.348 kWh/m^2/day. With this incidence energy, 1 kWp of the PV array will supply 3.06 kWh/day (70.4%) 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 follows: 0.25 kWh/kWp/day (5.8%), 0.65 kWh/kWp/day (15%), and 0.38 kWh/kWp/day (8.7%), respectively. From Fig. 10, 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 0.704 (70.4%), 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 0.968 (96.8%). Fig. 11 which depicts the incidence irradiation distribution is realized by plotting the global incident energy in collector plane (in kWh per class of 20 W/m^2) against the global incidence energy in collector plane (in W/m^2). From Fig 12, it is observed that the variation of the effective energy at the output of the array (in MWh/day) as against the global incident energy in 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 which can be as a result of the effects of higher PV array temperatures at such incident energy values. Looking at Fig. 13, one can easily observe that the highest peaks of the effective energy at the output of the array 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 can also be seen in Figures 7 and 10. The batteries' state of charge daily distribution and the system loss diagram are presented in Figures 14 and 15.

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

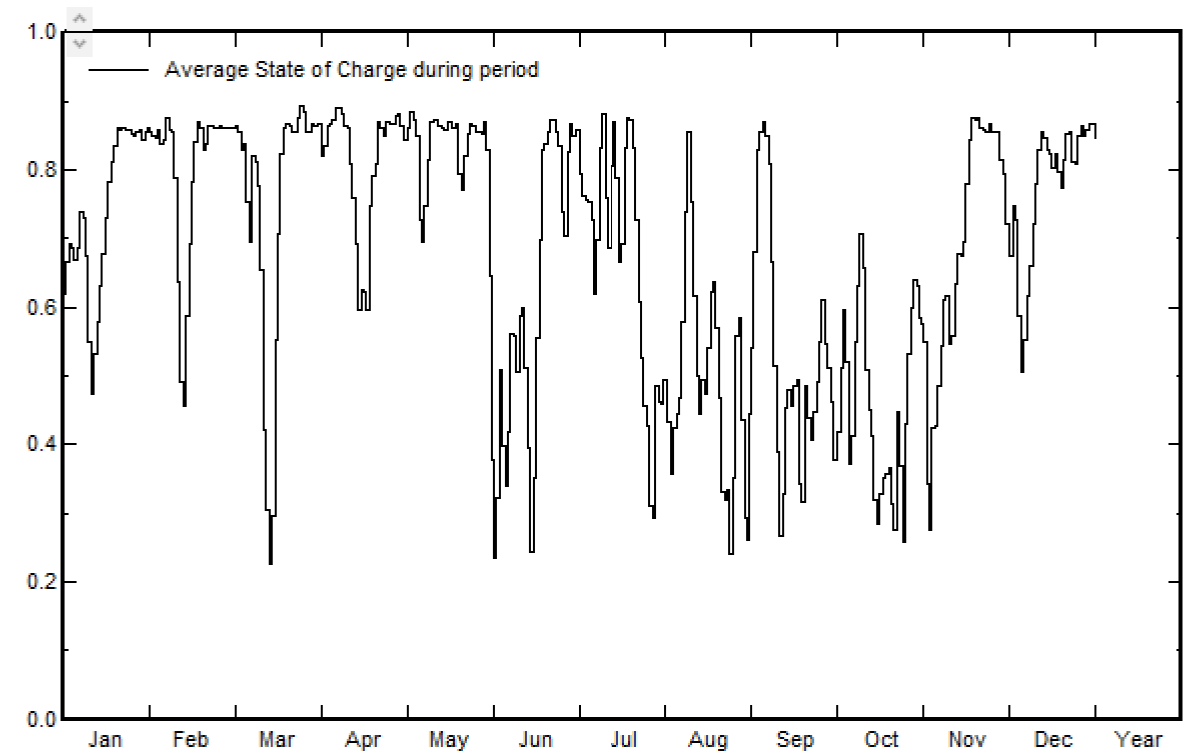

Fig. 14. State of Charge Daily Distribution

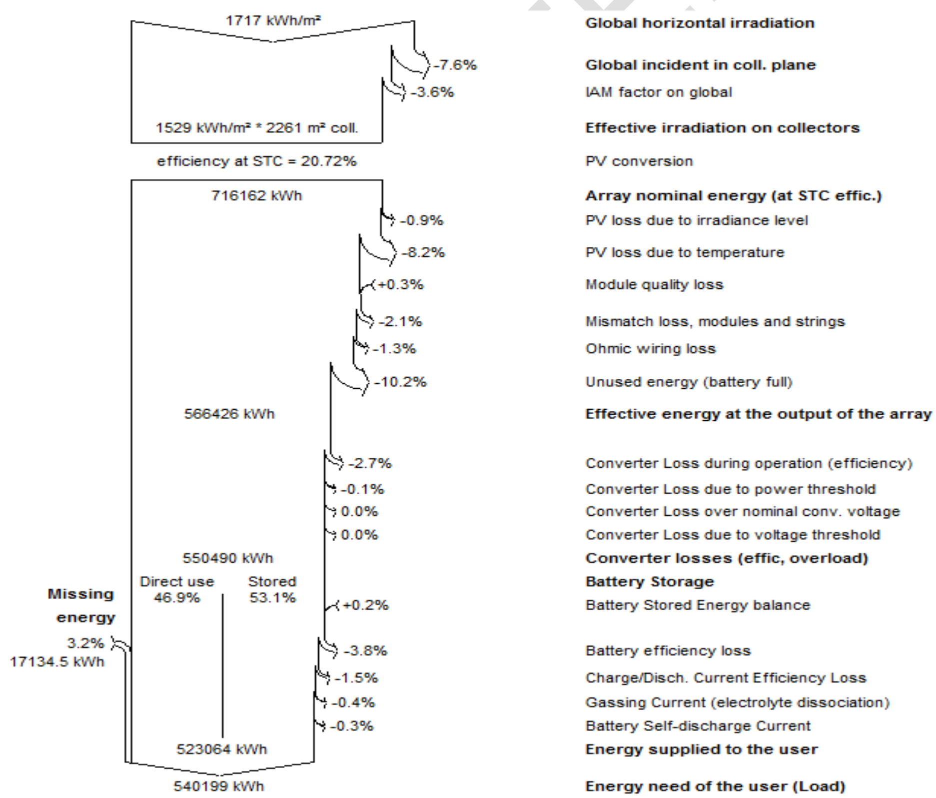

Fig. 15. System Loss Diagram

Table 7. Energy balances and main results

	GlobHor (kWh/m^2)	GlobEff (kWh/m^2)	E_Avail (kWh)	EUnused (kWh)	E_Miss (kWh)	E_User (kWh)	E_Load (kWh)	SolFrac (ratio)
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. System production and performance indices

System Production	Loss of Load	Battery Aging (State of Wear, SOW)
Available Energy = 615,168 kWh/year	Time Fraction = 3.1%	Cycles SOW = 94.1%
	Missing Energy = 17,134 kWh/year	
Used Energy = 523,064 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 performance ratio of 70.43% and a loss of load time fraction of 3.1%, 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 of the economic evaluation with no loan financing, 50% loan financing, and 80% loan financing are presented in Figures 16, 17, 18, and 19. The important economic results are summarized in Table 9.

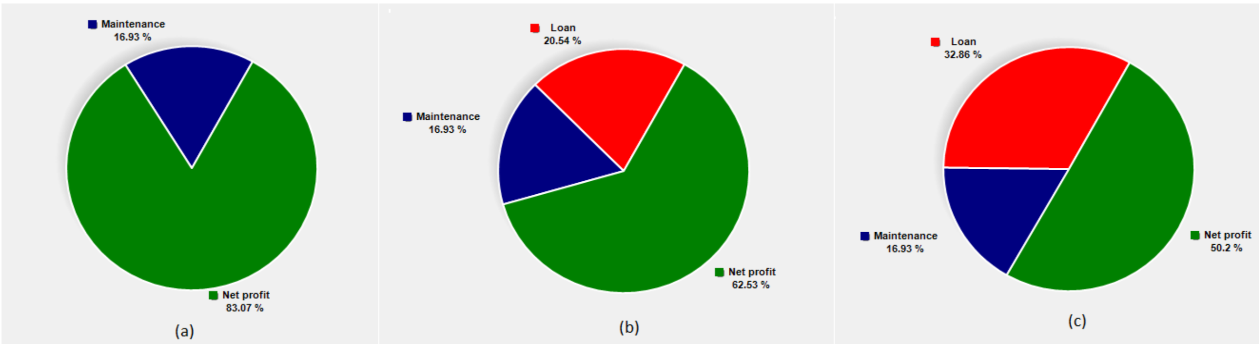

Fig. 16. Income allocation for (a) 0% loan financing, (b) 50% loan financing, and (c) 80% loan financing

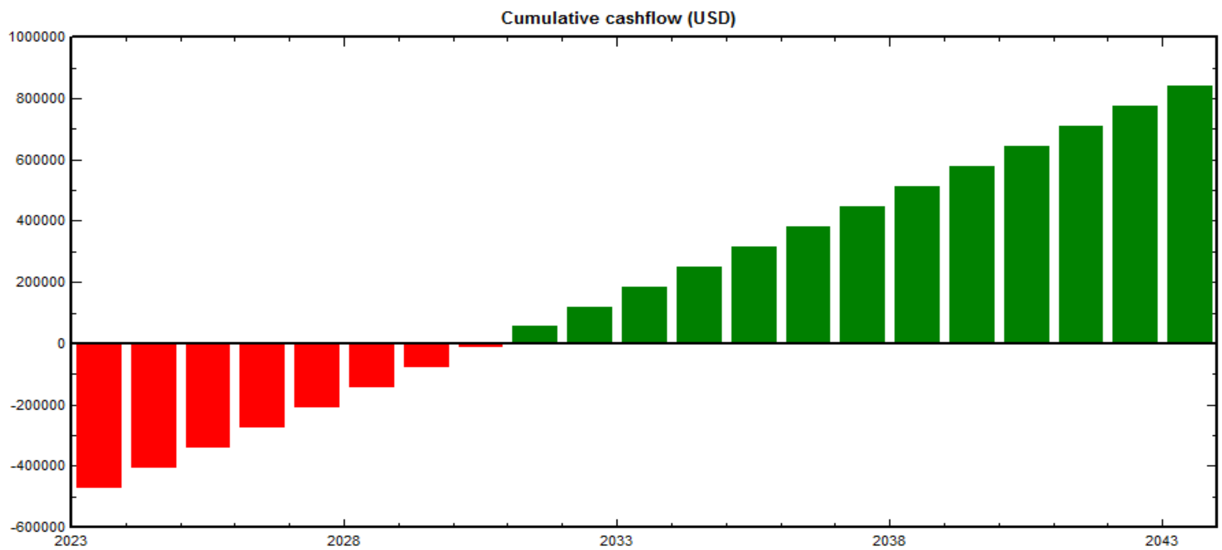

Fig. 17. Cumulative cash flow for 0% loan financing

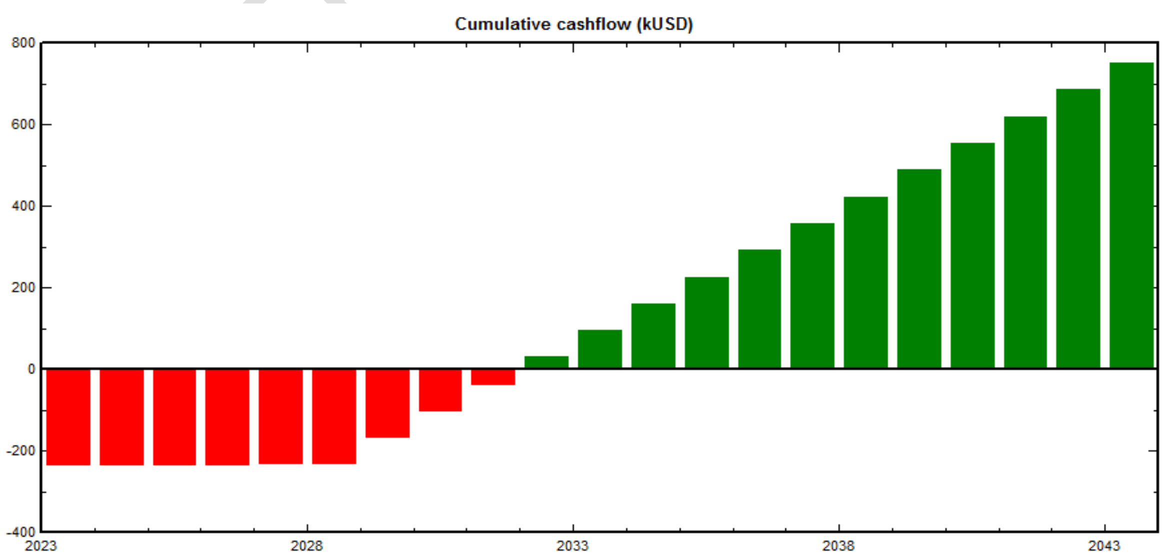

Fig. 18. Cumulative cash flow for 50% loan financing

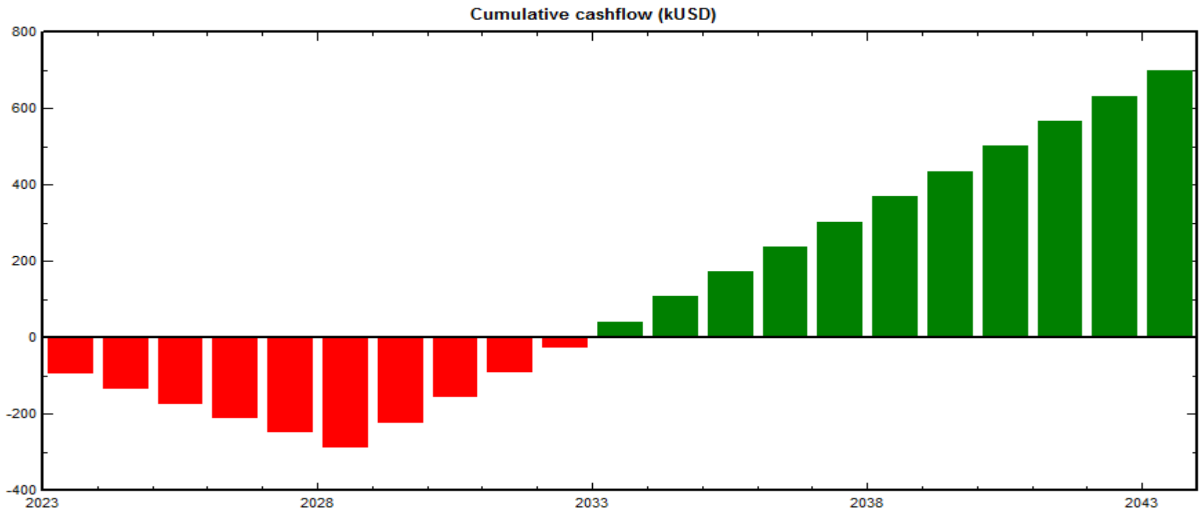

Fig. 19. Cumulative cash flow for 80% loan financing

Table 9. Summary of the economic evaluation results

Evaluation with 0% Loan Financing	Evaluation with 50% Loan Financing	Evaluation with 80% Loan Financing
Installation cost financing Own funds = 466,970.00 USD Loans = 0.00 USD Total = 466,970.00 USD	**Installation cost financing** Own funds = 233,485.00 USD Loans = 233,485.00 USD Total = 466,970.00 USD	**Installation cost financing** Own funds = 93,394.00 USD Loans = 373,576.00 USD Total = 466,970.00 USD
Expenses 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	**Expenses** 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	**Expenses** 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
Return on Investment 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%	**Return on Investment** 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%	**Return on Investment** 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 indices of the three financing considerations show that the project is feasible. The levelized cost of energy which is 0.0698 USD/kWh and 0.0.0784 USD/kWh for the 0% loan financing 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

A standalone PV solar power plant for a typical 200 bungalow housing estate in Owerri, Nigeria was designed and simulated to study its technical and economic feasibility using PVsyst 7.3 software. The design shows that with a global horizontal irradiation of 4.70 kWh/m2/day reaching Owerri, Nigeria, a 468 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 615,168 kWh (approximately 615 MWh) of electric energy 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.

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.

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