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Electrical and Environmental Performance Evaluation of a Stand-Alone Solar Power System

[a,b*]D. O. Akinyele, [b]D. Shomuyiwa, [c]J. O. Petinrin, [d]K. T. Alade
[a]Smart Power & Renewable Energy Systems Group,
Victoria University of Wellington, New Zealand
[b]Applied Energy Research & Concepts, Lagos, Nigeria
[c]Department of Electrical and Electronic Engineering,
Federal Polytechnic, Ede, Nigeria
[d]Department of Project Management Technology,
Federal University of Technology, Akure, Nigeria

Abstract- This paper discusses the electrical and environmental performance analysis of a stand-alone solar photovoltaic power system. The system is first modelled to suit a worst-case household energy requirement of ~16 kWh/d, using Agbado, Ogun State, Nigeria as a case study. The solar power system's performance is assessed by estimating its normalised annual yield and losses. Furthermore, due to the intermittent characteristics of the solar energy resource, the system's energy supply adequacy and reliability are examined through a detailed battery state of charge, annual unserved energy, loss of energy probability (LOEP) and the availability analysis. The environmental performance of the proposed system is examined in terms of the global warming potential (GWP), energy payback time (EPT) and the energy yield ratio (EYR). Results reveal that solar power system capacity ranging from 5.5 to 9 kW will be able to support the specified users' daily demand, with the unserved demand, LOEP and availability of 6.73 – 376 kWh/yr, 0.12 – 6.44% and 93.56 – 99.88%, respectively. The system's yield is 1,268 kWh/kW, while its losses are 462 kWh/kW. The proposed system's GWP, EPT and EYR are 8,720 kg CO_2-eq, 1.5 years and 16.62, respectively. Such results can be helpful in planning stand-alone solar PV systems.

Keywords: availability, battery state of charge, energy payback time, energy yield ratio, loss of energy yield.

1.0 Introduction

The cost of solar photovoltaic (PV) cells and modules has drastically reduced over the past few years. This factor, coupled with the solar energy resource availability and the ease of installation makes solar energy technologies a promising electricity option for Nigeria [1-5]. This is reflected in the several off-grid PV-based energy supply systems that have been installed in the country, such as those used to power households, offices, street lighting, community and health centers etc.

However, designing stand-alone solar photovoltaic systems requires a standard procedure that seeks to ensure a reliable electricity supply to the intended users [6-11]. Experience has shown that most photovoltaic systems that have failed in the country have not been carefully and properly designed. Also, the increased use of fossil fueled-based electricity in the country is not only increasing carbon footprint generation, but is also affecting the people's health. This paper is, therefore, motivated by this challenge by proposing a solar power system for residential applications, using Agbado area of the Ado-Odo Otta local government, Ogun State as a case study. Such a system has the potential to guarantee an eco-friendly energy supply for the users.

The study uses the guidelines specified in the global engineering standards and a practical knowledge in designing a stand-alone PV system that can support users' daily load demand of about 16 kWh. It employs the Hybrid Optimisation Model for Electric Renewables (HOMER) simulation tool to model the proposed system. It also evaluates the system's energy losses by using the design safety factor. The electricity generation system's performance is then assessed by calculating its normalised annual yield and losses.

Furthermore, due to the solar energy resource's variable characteristics [10-14], the proposed system's energy supply adequacy and reliability are examined through a detailed battery state of charge, annual unserved energy, loss of energy probability (LOEP) and the availability analysis. The environmental performance of the proposed system is examined in terms of the global warming potential (GWP), energy payback time (EPT) and the energy yield ratio (EYR).

The results of the paper are assessed by comparing them with some existing values in the literature. Such research outputs can be helpful in planning reliable stand-alone solar photovoltaic systems for Nigeria, including other developing countries. The remaining part of the paper is organised as follows: Section 2 focuses on a brief background, while section 3 discusses the methodology, Sections 4 and 5 present the results and discussion, and the conclusion.

2.0 Background

This study designs and evaluates the electrical and environmental performance of a stand-alone solar photovoltaic system, using a house in Agbado, Ogun State, Nigeria as a case study. It assumes a users' daily energy requirement of 16 kWh, which has previously been mentioned in [14]. This load profile for the energy consumption is shown in Fig. 1, which was designed for a three-bedroom flat. The electrical appliances that the proposed energy system will support include the lighting bulbs, television, DVD player, fans, fridge and the electric kettle.

It can be seen that the load pattern has three peak electricity demand periods viz. between 6 and 7a.m., at 1 p.m. and between 6 and 7 p.m. [14]. In the morning, energy is consumed for lighting, water boiling, and operating a TV and DVD player. The peak electricity demand in the afternoon is, however, as a result of operating the TV and the electric iron. In the evening, all the appliances are operated, except the electric iron. As shown in Fig. 1, the minimum, peak and the average loads are 0.25, ~1.64 and ~0.7 kW, respectively. In addition, the solar irradiation and ambient temperature of the location is shown in Fig. 2 [15].

The study in [14], however, does not discuss energy losses and load growth. It does not also consider the battery state of charge and reliability analyses. The focus of this current paper is to fill the identified knowledge gaps, while using the existing load profile. Undoubtedly, such system analysis will be useful for better understanding of how to design and model stand-alone PV systems in the country.

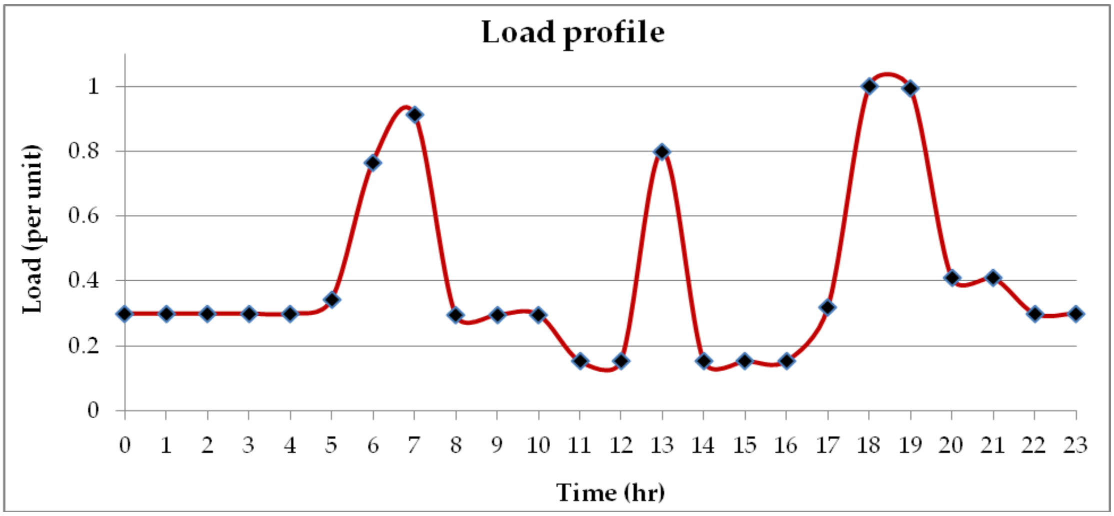

Fig. 1. Load profile

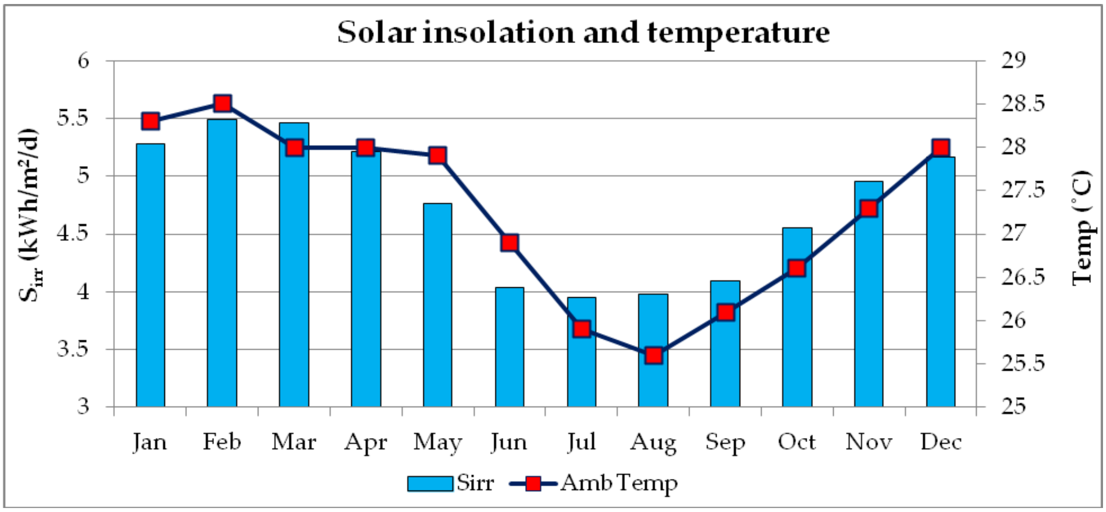

Fig. 2. Solar insolation and ambient temperature

3.0 Methodology

3.1 Solar PV array

The PV system's capacity can be determined by Eq. (1) [8]:

$$PV_c = \left(\frac{D}{S_{irr}}\right).D_{sf} \tag{1}$$

where D, S_{irr}, and D_{sf} represent the users' daily demand, the location's lowest monthly average solar irradiation and the design safety factor. An annual load growth rate of 1% is assumed in this paper. The D_{sf} quantifies the capacity that compensates for the losses to ensure the specified users' demand is adequately supported. The value of Eq. (1) without the D_{sf} is the system's ideal capacity, which is not sufficient to support the users' demand.

The system's output after considering losses can be estimated by Eq. (2) [6-10, 27, 28]:

$$PV_o = \frac{G_a}{G_{STC}}\left[\mathrm{x}.P_{\max}.\mathrm{y}\left(1+z(\mathrm{T}_c - T_{c,STC})\right)\right] \tag{2}$$

where x, y, z, G_a, G_{STC}, P_{max}, T_c and $T_{c,STC}$ represent the number of solar PV modules, PV de-rating factor, module's power temperature coefficient, the location's solar irradiance (W/m^2), solar irradiance at STC (1000 W/m^2), PV module's maximum power (W), actual cell temperature (˚C) and the cell temperature (˚C) at STC, respectively. The module's temperature can be calculated by Eqs. (3) and (4) [6-10].

$$T_c = T_a + \beta.G_a \tag{3}$$

$$\beta = \frac{NOCT - 20°C}{G_r} \tag{4}$$

where $NOCT$ and G_r represent the nominal operating cell temperature and the reference solar irradiance of 800 W/m^2, respectively. The $NOCT$ is the module's temperature at T_a = 20˚C, G_r = 800W/m^2 and wind speed = 1m/s [6-10]. Also, a de-rating factor of 0.8 is used in this study.

The PV system's yield and losses are estimated by Eqs. (5) and (6), respectively [16-18].

$$PV_y = \frac{PV_o}{PV_c} \tag{5}$$

$$PV_l = PV_c - PV_o \tag{6}$$

3.2 Battery storage system

The battery storage system's capacity is determined by Eq. (7) [7, 9, 18].

$$B_{sc} = \frac{D \times A_d}{\eta_r DoDV_s} \tag{7}$$

where A_d, η_r, DoD and V_s are the days of autonomy, battery's round-trip efficiency, depth of discharge and system's voltage, respectively. In this study, a DoD of 50% is used. This is in accordance with the Trojan battery system design [19]. In addition, the battery bank's maximum DoD of 70% is used for the analysis. This implies that the minimum state of charge (*SoC*) of the battery is 30%. This is to ensure that the battery bank has enough capacity to manage the disparity between the solar energy generation and the users' load demand.

3.3 System reliability

The energy balance of the proposed PV system can be determined by Eq. (8) [7, 9, 18]. The energy difference (E_{df}) can either be positive or negative. It is positive when the electricity produced by the PV system is more than the users' demand. However, a negative value is obtained when the electricity generated by the PV is less than the users' energy requirement. In the first case, there is energy excess, while there is deficit in the second case. The implication of energy deficit is that a loss of energy supply will be experienced by the intended energy consumers.

$$E_{df} = \sum_{i}^{8760} (PV_o - D)_i \tag{8}$$

The loss of energy probability can be calculated by Eq. (9), which is the ratio of the unserved energy to the total users' demand, over the year. The system's availability is evaluated by Eq. (10).

$$LOEP = \frac{\sum_{i=1}^{8760} (\text{Unserved}_{energy})_i}{\sum_{i=1}^{8760} (\text{D})_i} \tag{9}$$

$$PV_{av} = 1 - LOEP \tag{10}$$

3.4 Environmental analysis

3.4.1. Life-cycle carbon emissions

The PV system's life-cycle carbon emission is estimated by Eq. (11) [20-22]:

$$CF = \frac{\sum_{j \in GHG} \mu_j . CE_j}{PV_o} \tag{11}$$

where index j stands for the species of emissions that belong to the GHG family; μ_j is the GWP factor that corresponds to the species of emissions j; CE_j represents the cumulative emissions of species j during the PV system's life cycle; PV_o stands for the annual electricity production by the system.

3.4.2 Cumulative energy demand

The cumulative energy demand (CED) expresses the energy requirements over the solar PV system's life cycle. This energy is usually expressed or valued as primary energy. The primary energy and the CED can be defined as follows [22-25]:

- Primary energy - the energy embodied in natural resources that has not gone through any anthropogenic conversion process and needs to be transformed and transported to become a useful energy.
- Cumulative energy demand – the total energy demand that is valued as primary energy over the PV system's life cycle. It is estimated by Eq. (12).

$$CED = E_{ma} + E_{tr} + E_{in} + E_{op} + E_{de} \tag{12}$$

where E_{ma}, E_{tr}, E_{in}, E_{op} and E_{de} stands for the primary energy demands for manufacturing, transporting, installation, operation and decommissioning, respectively. The primary energy requirement for manufacturing is also known as the embodied energy of manufacture, and it is reported to be responsible for > 90% of the PV system's life cycle emissions.

3.4.3 Energy payback time

This environmental performance indicator is used to quantify the time required to compensate for the total primary energy, i.e. renewable and non-renewable energy requirements, over the system's life cycle. It can be estimated by Eq. (13).

$$EPT = \frac{CED}{PV_o} . \eta_g \tag{13}$$

where η_g is the average primary energy-to-electricity conversion efficiency at the load side.

3.4.4 Energy yield ratio

This parameter measures how many times the proposed photovoltaic system, would over its lifetime, generate the CED for its manufacture. It is also known as the energy return on investment (EROI). It can be estimated by Eq. (14)

$$EYR = \frac{PV_{lt}}{EPT} \tag{14}$$

where PV_{lt} is the PV system's lifetime. A 25-year lifespan is assumed in this study. An EYR > 1 implies that the energy generated over the PV system's operational life is larger than the energy that is initially invested in the production of the PV modules. This indicates that the proposed PV system has a higher net energy production. On the other hand, an EYR < 1 shows that the system is not a renewable technology. This its CED is more than the energy it generates during the life cycle.

4.0 Results and discussion

4.1 Electrical performance of the solar PV

4.1.1 Solar PV capacity and output

The system's ideal capacity is 4.05 kW. This PV size produced no feasible result when simulated in HOMER. This is because it is not sufficient to support the users' demand of 16 kWh/d. Fig. 3 shows the different system ratings that can power the specified load and their respective annual energy outputs.

The sizes range from 5.5 to 9 kW and their corresponding annual energy production ranges from 6,976 to 11,416 kWh, while the energy losses range from 2,540 to 4,155 kWh. Since the different PV capacities are simulated under the same design parameters earlier presented in the methodology section, they will have the same normalised yield and losses [17, 18, 22]. Therefore, the yield and losses of the solar PV systems are about 1,268 and 462 kWh/kW, respectively.

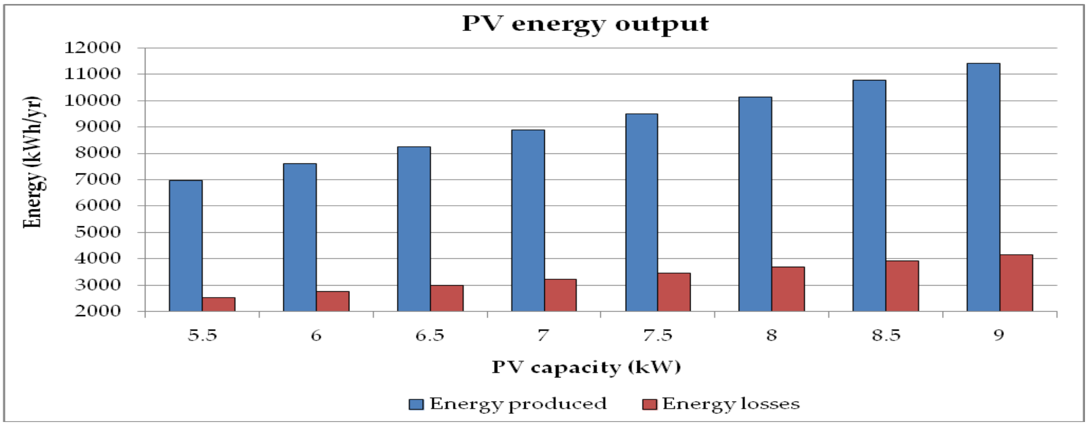

Fig. 3. Solar PV annual energy output

4.1.2 Battery and inverter systems

The proposed system's battery capacity is 1,176 Ah. This has been obtained with autonomy, round-trip efficiency, DoD and system voltage of 1.5, 0.85, 0.5 and 48 V, respectively. An Hoppecke 6 OPzs 600 battery type was selected from the HOMER library, which a 2V 600 Ah cell. 48 units of this cell are configured in two strings, i.e. 24 units/string. In addition, an inverter size of 3 kVA is simulated for the application.

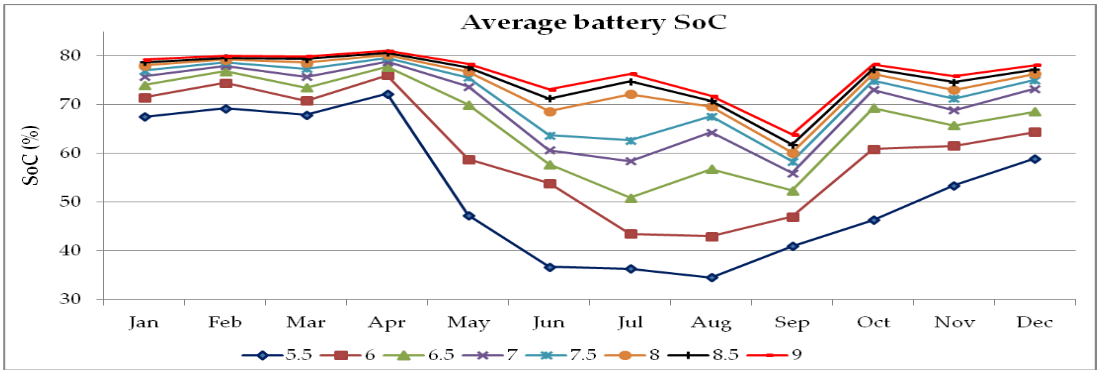

Fig. 4. Monthly average battery state of charge

The monthly average lowest battery SoC values are presented in Fig. 4, with the corresponding solar PV system capacities. It can be seen that the 5.5 kW PV system has the lowest battery SoC values, while the 9 kW system has the highest values. This is because the higher the PV capacity, the higher the charging current that is available to the battery bank. The average values shown in Fig. 4 meet the battery constraints of $30\% \leq$ battery SoC $\leq 100\%$.

4.1.3 System reliability

The unserved energy for the specified PV systems are 376, 188, 105, 59, 31, 21, 13 and 6.73 kWh/yr, respectively. The loss of energy probability and the availability are shown in Fig. 5. The LOEP ranges from 0.12 to 6.44%, while the availability ranges from 93.56 to 99.88%. The results show that the higher the PV capacity, the higher the availability.

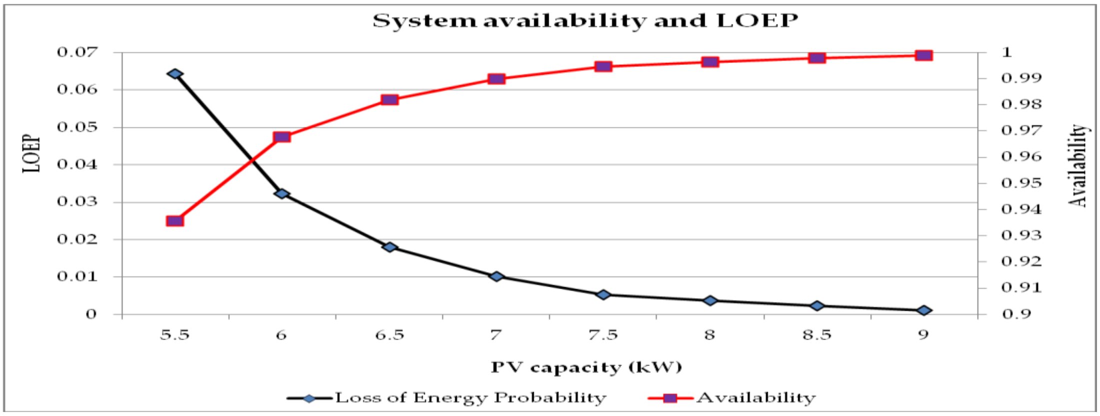

Fig. 5. System reliability

From the electrical performance and reliability point of view, the 9 kW solar PV system is the best option for electrifying the house. However, it will have the highest cost. The 5.5 kW system will have the optimum performance, i.e. it will have the lowest initial capital cost. The 6.44% loss of energy by this system indicates that the users will experience loss of energy hours of 564 in a year. This translates to 23.5 days in a year. Using a petrol or diesel generator during such periods will produce less environmental impact compared to the scenario of using 100% diesel generator. Therefore, the 5.5 kW is a suitable PV design for the house.

In addition, while Fig. 4 is the average SoC values, Fig. 6 shows the hourly battery energy profile. Such a profile provides a better view of the battery SoC and it can be seen that the battery bank's minimum SoC of 30% is reached many times from May to November for the PV only option. This means that a loss of energy will be experienced during those periods when the SoC goes below 30%.

By operating a 3 kVA generator during those periods with a low solar irradiation cycle, the battery SoC profile is improved. The generator is operated for 276 hr per year (i.e. 11.5 days in the year). The energy generation of the PV and the generator is 6,976 and 1,104 kWh/yr, respectively. The renewable energy fraction is 85%, while thate of the fossil-fuelled generator is 15%. Also, the loss of energy probability and the availability is 0 and 1, respectively. Though hybrid energy configuration is not the focus of this study, we have presented the analyses in Figs. 6 and 7 to how trade-offs can be allowed between system size, cost and reliability. It is assumed that most of the houses in the specified have a petrol or diesel generator and a 5.5 kW system with a 3 kW can provide a reliable energy supply for the house, rather than the 9 kW PV system.

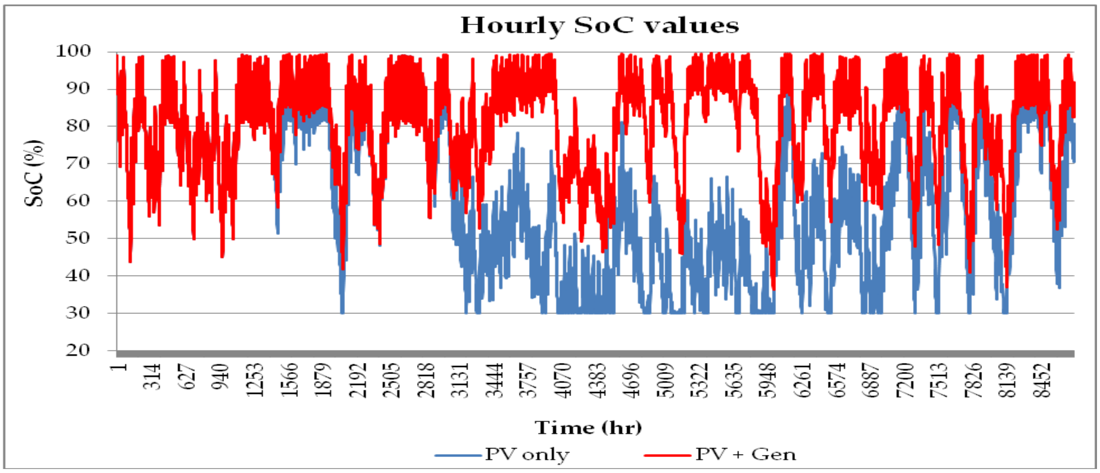

Fig. 6. Hourly battery profile

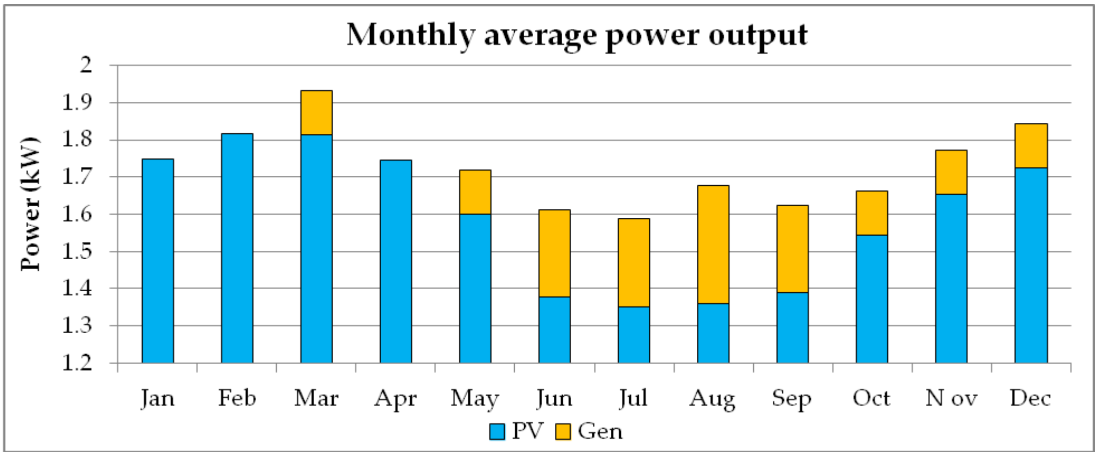

Fig. 7. System's power output

4.2 Environmental performance of the solar PV

A solar PV technology's life-cycle emission rate of 50 gCO_2/kWh is assumed in this study for crystalline solar technologies, based on the values reported in [20]. This value is assumed because there is currently no solar cell manufacturing plant in Nigeria and most PV modules are imported from Asia, Europe and the US [20-25]. The PV system's emission rate is thus used to estimate the GWP. The GWP is 8,720 kg CO_2-eq, which can be compared with a value of ± 6,000 kg CO_2-eq reported in [20]. Furthermore, the emission rate of 50 g CO_2/kWh is very small compared to that of the conventional energy generation systems. Renewable energy technologies have life cycle emission rates that are about 400 to 1,000 g CO_2/kWh less than the values for the conventional energy systems [26]. A value ranging from 576 to 695 gCO_2/kWh was reported for a diesel power system in [22].

Furthermore, a cumulative energy demand of 4,350 MJ eq. is used in this paper, according to a previous study in [22]. This translates to 1,208.33 kWh. The value of E_{aGEN} per module is 241 kWh/yr, while an η_g of 30% is assumed. The solar PV system's EPT is 1.5 years. The result demonstrates that it will take the PV system 18 months to pay back the energy used for its manufacture. The EPT obtained in this study can be compared with values ranging from 1.38 to 1.51 years reported in [23] for different locations - Philippines, Europe, Korea, Malaysia and USA.

With a system's lifetime of 25 years, the EYR is 16.62. This indicates that the stand-alone energy system can generate 16.62 times as much energy during its life cycle, as it takes to manufacture it. This value can also be compared with the values of 12.6 and 16.1 reported in [21] for China and Europe, respectively.

5.0 Conclusion

This paper has discussed the electrical and environmental performance evaluation of a stand-alone solar photovoltaic power system. The system was modelled to support a worst-case household load demand requirement of ~16 kWh/d, using Agbado, Ogun State, Nigeria as a case study. Its performance is assessed by estimating the normalised annual energy yield and losses. The system's electricity supply adequacy and reliability have been analysed through the battery state of charge, annual unserved energy, loss of energy probability and the availability indicators. The environmental performance of the proposed system was presented in terms of the global warming potential (GWP), energy payback time (EPT) and the energy yield ratio (EYR).

The research results revealed that the system capacity ranging from 5.5 to 9 kW will be able to meet the users' daily demand. The unserved demand, loss of energy probability and the availability are 6.73 – 376 kWh/yr, 0.12 – 6.44% and 93.56 – 99.88%, respectively. Also, the PV system's yield is 1,268 kWh/kW, while its losses are 462 kWh/kW. The system's GWP, EPT and EYR are 8,720 kg CO_2-eq, 1.5 years and 16.62, respectively.

This study has presented a practical design and analysis of a stand-alone PV system based on the global engineering standards and field experience. Such an analysis can be useful for planning solar PV systems for off-grid applications in Nigeria, and other developing countries.

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