

Performance Evaluation of the Navrongo Solar PV Power Plant in Ghana

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Abstract: The electric power-driven economy of Ghana has necessitated the continual balance of demand with supply by making use of economically feasible sources of energy. In this paper, a 2.5 MW grid connected solar photovoltaic (PV) power plant in Navrongo is evaluated for its performance in 2014. The plant's output energy, including PV modules, and system efficiencies with other performance indicators were analysed based on IEC 61724 standard. The average ambient and PV module temperature determined was 31°C and 45°C respectively, with 514 W/m² as the average global radiation. The monthly daily average energy generated was 10.7 MWh with 320.5 MWh and 3845.8 MWh as total monthly average and annual generated energy respectively, during the period. The respective average array, reference, and final yields in hours per day (h/d) were 0.48, 0.51 and 4.13 as well as 18% Capacity Factor, and 81% Performance Ratio. A total of 3768.0 MWh was delivered and the PV modules, inverter and system efficiencies were 10.1%, 84%, and 10.3% respectively. In conclusion, it was identified that, dust accumulations on the PV modules surface, significantly reduces the output power due to inefficient use of solar irradiation. Effective and efficient cleaning of the PV modules surface is therefore recommended for improved efficiency of the plant. The aim of this research; therefore; which was to evaluate the performance of the Navrongo solar PV power plant and optimise the energy output efficiently by the use of modelling and simulation has been achieved.

Keywords: Photovoltaic System, Performance Evaluation, Renewable Energy

1. Introduction

In recent times, the importance of energy to economic development is as vital as the need of air to sustain life. Every single activity is more or less dependent on energy. The demand for energy in Ghana is increasing exponentially, a consequence of population and industrial growth.

Over the past years, Ghana has relied on hydro and thermal power to meet her energy needs. This implies that, the possibility of power crisis in the country is predictable once our water levels go down or supply of gas from the West Africa Gas and Ghana Gas Company is cut. Shortage of power has reoccurred so many times in Ghana's history leading to load shedding activities as the last resort available to the utility company to balance electricity supply and demand in the country [1]. Presently, as a result of low energy production,

there is a nationwide load shedding activity. A situation which hampers economic development and investor confidence even though, government is making serious efforts to bring the situation to normalcy.

Ghana has an installed electricity generation capacity of 2831 MW with about 55.8 per cent recorded in April 2016 as coming from large hydro plants [2]. Volta River Authority (VRA) generates 75 per cent of Ghana's electricity [3]. The Government has plans to increase the capacity to 5,000 MW in the near future including renewable energy sources. Consequently, renewable energy power (REP) Act 2011 was enacted in December 2011 to provide the legal framework for the development of renewable energy. Subsequently, VRA has taken a bold initiative of building a 2.5 MW grid connected Solar photovoltaic (PV) Plant at Navrongo in an effort to augment the power generation from renewable energy sources [2].

BXC Company Ltd, a subsidiary of BXC Beijing China, followed VRA's strategic initiative and is currently operating a 20 MW solar PV power generating plant at Gomoa Onyadze in the Central Region of Ghana on test trial. A project, described as the largest solar PV farm in West Africa is capable of serving over 20000 homes with electricity when in full operation [4]. With several other similar projects to come on-board, private investors, Mere Power Nzema Limited (MPNL) is awaiting Government Consent and Support Agreement (GCSA) to commence its 155 MW grid connected solar PV power plant project in the Western Region of Ghana [5].

Other researchers have looked at performance evaluations of PV systems including: Fetyan and Hady, Esmailion *et al.* and Kymakis *et al.* published monitoring PV performance results to demonstrate the performance of system components, energy production, loss mechanisms associated with system operation, reliability and causes of system failures as well as validity of theoretical models using measured data, and long-term system performance [6, 7, 8].

1.1. The Overview of the Navrongo Solar PV Power Plant

The Navrongo Solar PV Plant, since the time it was commissioned in April, 2013, has been in operation except for some few hours of down-time for maintenance purposes. The energy performance of the PV plant and its overview are shown in Figure 1 and Figure 2 respectively [9].

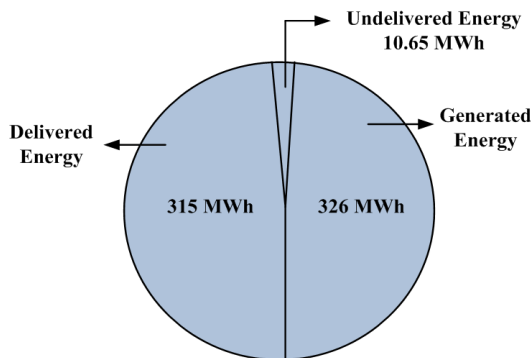


Figure 1. Pie Chart of Energy Generated, Delivered and Undelivered in MWh for January, 2014.

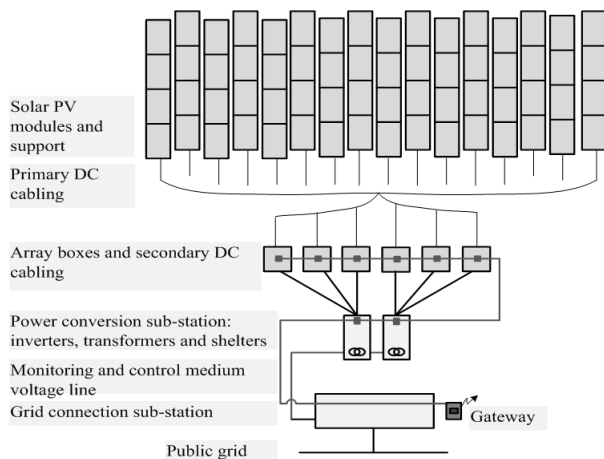


Figure 2. Overview of the Navrongo Solar PV Power Plant System.

As revealed in Figure 1, considerable amount of the energy generated in the month of January, 2014 was not delivered to the grid. This undelivered energy includes losses which need to be investigated. Achieving optimal performance is next to impossible without monitoring of the efficiency of PV systems [10]. Therefore, this research is intended to evaluate the performance of the Navrongo solar PV power plant and recommend for more efficient performance.

1.2. Renewable Energy Policy of Ghana

The reduction of fossil fuel resources around the world has imposed an urgent search for alternative energy sources to meet the present-day demands. Subsequently, the global interest in renewable energy (RE) has heightened in recent times with much attention being given to solar energy which is clean, unlimited and environmentally friendly, among other RE options [11].

Ghana is well endowed with RE resources. The monthly average solar irradiation is between 4 and 6 kWh/m²/day, with sunshine duration between 1800 and 3000 hours per annum offering very high potential for grid connected and off-grid applications. However, till recently, little was done to exploit this resource for grid connected power generation.

One of the objectives of the RE Policy of Ghana is to increase the contribution of RE sources (including hydro, solar, biomass and wind) to 10% for grid, mini grid and off-grid applications; by 2020. Solar power has considerable potential to serve households in villages that have no access to electricity supply from the national grid [12].

1.3. Solar Radiation in Navrongo

The success of any solar energy installation depends largely on the availability of solar radiation at that location, making detailed knowledge of solar resource data critical for planning and siting.

Navrongo, the administrative capital of the Kassena Nankana East District of Upper East Region of Ghana, is an important market town known for its cathedral and grotto. It has a flat terrain and ecology that is typical of the sahel areas with solar intensity of 4 – 6.5 kWh/m²/day which is by far, the highest in Ghana making the area suitable for the solar PV power plant project [13].

1.4. Grid-Connected PV System

Manukumar *et al.* defines electrical grid as interconnected network for delivering electricity from suppliers to consumers [14]. It consists of generating stations that produce electrical power, high-voltage transmission lines that carry power from distant sources to demand centers and distribution lines that connect individual customers. The grid can be considered as a large sink of energy, wherein energy generated by solar PV can be supplied or taken from when required. The idea of connecting PV system to the grid is to use the grid as energy storage medium so that the use of battery can be avoided [15].

Grid connected PV systems can broadly be classified into small and large power applications. Figure 3 gives a summary

of types of PV system. This research work focuses on grid connected PV system for large power applications [16].

Klaus *et al.* stated that grid connected PV systems for large power applications are mainly designed to act as power plants to generate power which is supplied to the grid [13]. They are grouped as the systems connected to distribution grid and the one connected to transmission grid.

According to Solanki, S. S., medium to large size (100 kW –

1 MW) grid connected solar PV power plants are used to feed power to the local power distribution grid [17]. The distribution grid is employed to supply power to small village(s), large industry and also industrial complex. Large to very large size (1 MW – 100 MW) grid connected solar PV power plants are used to feed power to the main alternating current (AC) transmission or generation grid.

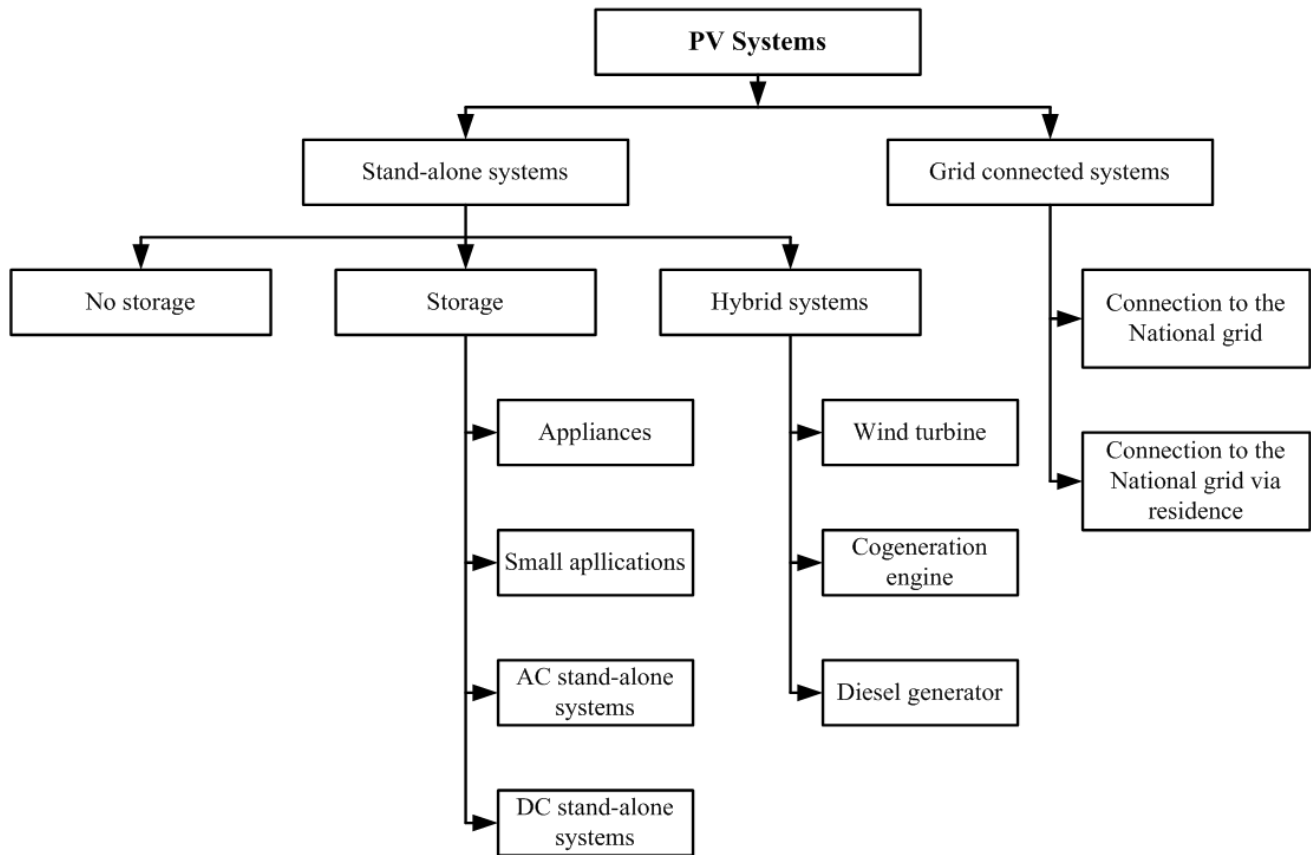


Figure 3. Types of PV Systems.

1.4.1. Basic Components of Grid Connected PV System

Although, solar modules are the heart of a PV system, many other components termed as balance of system (BoS) are required for a working PV system [15]. Grid connected PV system essentially comprises the following components:

- i) PV modules/array which can either be connected in series or parallel with mounting frame to provide solar PV power;
- ii) PV array combiner or junction box with protective equipment;
- iii) DC and AC cabling;
- iv) DC main disconnect/isolator switch;
- v) DC-DC converter;
- vi) Inverter used to convert DC to AC;
- vii) Transformer to boost up the AC output voltage from the inverter;
- viii) Meter cupboard with power distribution system, supply and feed meter with electricity connection; and
- ix) instruments; and protection and earthing equipment.

The DC-DC converter is required to convert the module output, which will have a variable voltage depending on the time of the day and the weather conditions, to a fixed voltage output that is used as input for the inverter.

1.4.2. Working Principle of Grid Connected PV System

The electricity produced by PV array based on photovoltaic effect is most efficient during sunny periods [11]. At night or during cloudy periods, stand-alone PV power systems use storage batteries to supply electricity needs. With grid connected PV systems, the energy generated during the day is stored by the grid as long as it is available. An inverter converts DC produced by the PV array to AC and transformer step up the voltage level as required for export to the public electricity grid.

1.5. Conditions for Grid Interfacing

In order to connect the power output of solar PV system to the public electricity grid, some conditions must be satisfied to

ensure tolerable synchronisation of the two systems [11].

The conditions for proper interfacing between two systems can be determined from the phase sequence matching and the frequency matching. The phase sequence matching of the PV system with conventional grid should be harmonised for three phase system. The phases should be 120 electrical degrees apart from each other for both systems. The frequency matching of the solar PV system should be same as grid. Generally, the public electricity grid of Ghana is of 50 Hz frequency capacity. Now, if solar PV systems' frequency is within a tolerance of $\pm 5\%$, then synchronisation is possible but the solar PV system frequency should not be less than the grid frequency [18]. Another important condition is voltage matching. Voltage level of both the solar PV and grid systems should be same, otherwise synchronisation is not possible.

2. Materials and Methods

This section of the paper presented the technical and meteorological description of the solar PV plant being evaluated at Navrongo. It continues with mathematical models leading to the evaluation of the PV power plant's performance. Some principal PV system parameters base on which the Navrongo Solar PV System is evaluated is therefore, presented.

2.1. Description of the Navrongo Solar PV System

The system is a 2.5 MW grid-connected PV power plant made up of 8622 SunTech and Jinko PV modules rated at 295-Watt peak per module. The modules are connected to form arrays and mounted on a fixed stainless-steel support structure facing south at tilt angle of 130° to the horizontal. The total array size is $16,899.16 \text{ m}^2$ within a land space of 477 hectares. The system has five Guanya Power manufactured grid-connected central inverters with power rating of 500 kW which are supplied with dc power from the PV arrays through collector control boxes.

Through different levels of system protection, the output of the inverters is fed to a 415 V AC bus, which feeds the primary of a 415/34.5 kV multipurpose transformer through a central circuit breaker. The output of the transformer through another circuit breaker is fed to the Pungu sub-transmission line. Figures 4 show a sectional view of the arrays respectively at the Navrongo solar power station [19]. The system uses Supervisory Control and Data Acquisition (SCADA) system for data acquisition and control operations.



Figure 4. Sectional View of the Navrongo Solar PV Array.

2.1.1. System Location

The following information describes the location of the solar PV plant used as a case study of this research endeavour: i) Administrative Region: Upper East; ii) Administrative District: Kassena Nankana East; iii) Administrative Town: Navrongo; iv) Site address: Pungu Telania (4.77 ha size of land); and v) Global Positioning Systems (GPS) coordinates: $10^\circ 55' 28.10'' \text{ N } 01^\circ 03' 24.90'' \text{ W}$; $10^\circ 55' 36.50'' \text{ N } 01^\circ 03' 16.80'' \text{ W}$; $10^\circ 55' 28.50'' \text{ N } 01^\circ 03' 10.60'' \text{ W}$ [19].

2.1.2. Annual System Design Performance Parameters

The following specifications were provided by the project equipment manufacturer with an annual solar irradiation in optimal plane of modules without any shadow: 5.53 $\text{kWh/m}^2/\text{day}$; ii) Installed capacity of the plant: 2.5 MWp; iii) Grid connection distance: 10 km; iv) Net electricity generation measured at the output substation: 3183 MWh/year; v) Performance ratio: 80; vi) Number of PV modules: 8662; vii) Watt-peak of one PV module: 285 – 295 Watt peak (Wp); viii) Number of inverters: 5; ix) Power of inverters: 500 kW; x) PV array: fixed; xi) Monitoring equipment: electricity meters at substation; and xii) Average lifetime: 20 – 25 years [19].

2.1.3. Meteorological Station Description

The Meteorological station is located within the PV arrays' yard and has the fundamental functions of sensing and measuring the weather conditions in the premises of the PV Power Station. Important parameters including global radiation, direction of wind and its velocity and ambient temperature are recorded hourly at the station. Figure 5 shows a solar PV powered meteorological station at the Navrongo Solar Power Plant's yard [19].



Figure 5. Solar PV Powered Meteorological Station.

2.1.4. Methods and Tools

Methods employed in this research mainly include

Microsoft Excel based data analysis of field data and simulation of Mathematical models in MATLAB/Simulink for optimisation purpose. The field data which is taken as secondary data was recorded in an hour interval for 11 hours per day from 6 a.m. to 5 p.m. in the year 2014. The data primarily include environmental data, inverter and transformer output data as well as the Plant's energy output values. The plant's performance is therefore evaluated using the PV system parameters described in section 2.2.

2.2. Important PV System Parameters

2.2.1. Energy Output

An important parameter for characterising a PV system is the energy yield. This is of a major interest to end users who are concerned of deriving maximum energy (kWh) and profit from the system. The total daily ($E_{AC,d}$ & $E_{DC,d}$) and monthly ($E_{AC,m}$ & $E_{DC,m}$) for AC and DC energy generated respectively by a PV system is determined from the following:

$$E_{AC,d} = \sum_{t=1}^{t=y} E_{AC,t} \quad (1)$$

$$E_{AC,m} = \sum_{d=1}^N E_{AC,d} \quad (2)$$

$$E_{DC,d} = \sum_{t=1}^{t=y} E_{DC,t} \quad (3)$$

$$E_{DC,m} = \sum_{d=1}^N E_{DC,d} \quad (4)$$

where, N is the number of days in the month and t is the number of time intervals in minutes in a day [20].

2.2.2. Array Yield

The array yield (YA) according to Kymakis *et al* is defined as the energy output from a PV array over a defined period (day, month or year) divided by its rated power as presented in equation (5) [8].

$$Y_A = \frac{E_{DC}}{P_{PV, rated}} \quad (5)$$

where, Y_A = array yield (kWh/kWp); $P_{PV, rated}$ = PV rated power (kWp).

The daily array yield ($Y_{A,d}$) and monthly average daily array yield ($Y_{A,m}$) are given as [14]:

$$Y_{A,d} = \frac{E_{DC,d}}{P_{PV, rated}} \quad (6)$$

$$Y_{A,m} = \frac{1}{N} \sum_{d=1}^N Y_{A,d} \quad (7)$$

where, $Y_{A,d}$ = daily array yield (kWh/kWp); $E_{DC,d}$ = total daily DC energy output (kWh); $Y_{A,m}$ = monthly average daily array yield (kWh/kWp); and N = number of days in the month.

2.2.3. Final Yield

The final yield is defined as the annual, daily or monthly net AC energy output of the system divided by the rated or nominal power of the installed PV array at STC. This is a representative figure that enables comparison of similar PV systems in a specific geographic region. It is dependent on the type of mounting, vertical on a façade or inclined on a roof and also on the location [21]. Equation (8) describes the final yield.

$$Y_{F,a} = \frac{E_{AC,a}}{P_{PV, rated}} \quad (8)$$

where, $Y_{F,a}$ = annual final yield (kWh/kWp); and $E_{AC,a}$ = total annual AC energy output (kWh).

The daily final yield ($Y_{F,d}$) and the monthly average daily final yield ($Y_{F,m}$) are given as:

$$Y_{F,d} = \frac{E_{AC,d}}{P_{PV, rated}} \quad (9)$$

$$Y_{F,m} = \frac{1}{N} \sum_{d=1}^N Y_{F,d} \quad (10)$$

where, $Y_{F,d}$ = daily final yield (kWh/kWp); $E_{AC,d}$ = total daily AC energy output (kWh); and $Y_{F,m}$ = monthly average daily final yield (kWh/kWp).

2.2.4. Reference Yield

The reference yield (Y_R) defines the solar radiation resource for the PV system. It is a function of the location, orientation of the PV array, and month-to-month and year-to-year weather variability. Y_R is the ratio of total in-plane solar insolation (G_m) divided by the total solar radiation on the PV array at STC (G_{STC}). It is the number of peak sun-hours according to Kymakis *et al* and is given as [8]:

$$Y_R = \frac{G_m}{G_{STC}} \quad (11)$$

where, Y_R is the reference yield (kWh/kWp).

2.2.5. PV Module Efficiency

Al-Adwan stated that, PV module conversion efficiency refers to the proportion of the input energy from the sunlight that is converted to power output of the module [22]. The efficiency depends on the type of PV cell and is also a common parameter used in comparing solar PV cells. Equation (12) is used in determining the instantaneous PV module conversion efficiency whiles the monthly PV module efficiency is found from equation (13).

$$\eta_{PV} = \frac{P_{DC}}{G_m A_m} \quad (12)$$

$$\eta_{PV,m} = \left(\frac{\bar{E}_{DC,d}}{G_m A_m} \right) \times 100\% \quad (13)$$

where η_{PV} is the instantaneous PV module conversion

efficiency (dimensionless) and $\bar{E}_{DC,d}$ the monthly average daily total DC output in kWh.

2.2.6. Performance Ratio

Verma and Singhal defined Performance Ratio (PR) as a measure of the quality in percentage of a PV plant which is independent of size and location hence, described often as a quality factor [23]. The PR establishes the relationship between the actual and theoretical energy output of a PV plant. It therefore shows the amount of the energy actually available to be exported to the grid after energy loss and of energy consumption for operation have been deducted. When PR value determined for a PV plant is closer to 100%, it is described to be more efficient in its operation. This implies more solar energy is converted to electrical energy when the PR value is higher [24].

The PR quantifies the overall effect of losses due to: inverter inefficiency, wiring, cell mismatch, elevated PV module temperature, reflection from the module front surface, soiling, system down-time, shading, and component failures [25]. Equations (14) and (15) can be used in determining the PR of a PV systems.

$$PR = \frac{\eta_{sys}}{\eta_{STC}} = \frac{E_{AC} G_{STC}}{G_m P_{DC,STC}} = \frac{E_{AC}}{G_m \eta_{STC}} \quad (14)$$

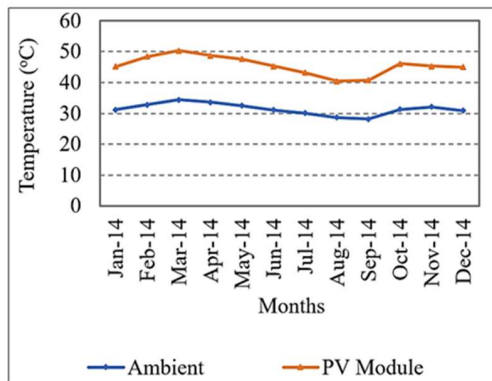
$$PR = \frac{Y_F}{Y_R} \quad (15)$$

where, $\eta_{sys} = \frac{E_{AC}}{A_a G_m}$, and $\eta_{STC} = \frac{P_{DC,STC}}{A_a G_{STC}}$

2.2.7. Capacity Factor

The Capacity Factor (CF) is a means used to present the energy delivered by an electric power generating system. If the system delivers full rated power continuously, its CF would be unity. Masters, defined CF as the ratio of the actual annual energy output to the amount of energy the PV system would generate if it operated at full rated power for 24 hours per day for a year and is given as:

$$CF = \frac{Y_{F,a}}{24 \times 365} = \frac{E_{AC,a}}{P_{PV,rated} \times 8760} = \frac{G_m \times PR}{P_{PV,rated} \times 8760} \quad (16)$$



(a)

CF for grid-connected PV system is given as:

$$CF = \frac{h_{ps,d}}{24} \quad (17)$$

where $h_{ps,d}$ is the peak sun hours in a day [21].

2.2.8. PV Cell Temperature

PV cells temperature is one of the most important parameters used in evaluating the performance of PV systems energy output. The PV cell temperature is influenced by parameters such as cell types, the thermal properties of the materials used, module configuration and local climate conditions.

The efficiency of PV module is significantly affected by its cells' operating temperature. Due to the tight manner in which PV Modules are encapsulated in order to protect them from environmental degradation, it is a difficult task to measure their cell temperatures. In most cases, the PV modules' back surface temperature is usually measured and considered in place of the cell temperature with assumption that, the two temperatures are close [26]. Ciulla *et al.* presented a simplified model for explicitly determining the PV cell temperature for a large-scale outdoor grid-connected PV power plant in equation 18 [27].

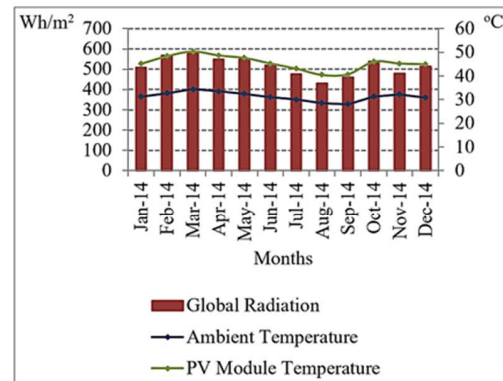
$$T_c = T_a + \frac{G_m}{G_{SOC}} \times (T_{NOCT} - 20) \quad (18)$$

3. Results and Discussions

3.1. Performance Evaluation Results

3.1.1. Influence of Global Radiation, Ambient and PV Module Temperature on Generated Energy

The computed PV module monthly operating temperature and the ambient temperature measured during daylight hours over the evaluation period is shown in Figure 6(a). The PV modules' operating temperature was determined based on equation 18. Results of the influence of global radiation on PV modules' temperature are also presented in Figure 6(b). Subsequently, the temperature and global radiation effect on the energy produced is revealed in Figures 7(a) and 7(b).



(b)

Figure 6. (a) Monthly Averaged Daily Ambient and PV Module Temperature; (b) Monthly Averaged Daily Irradiance, Ambient and PV Module Temperature.

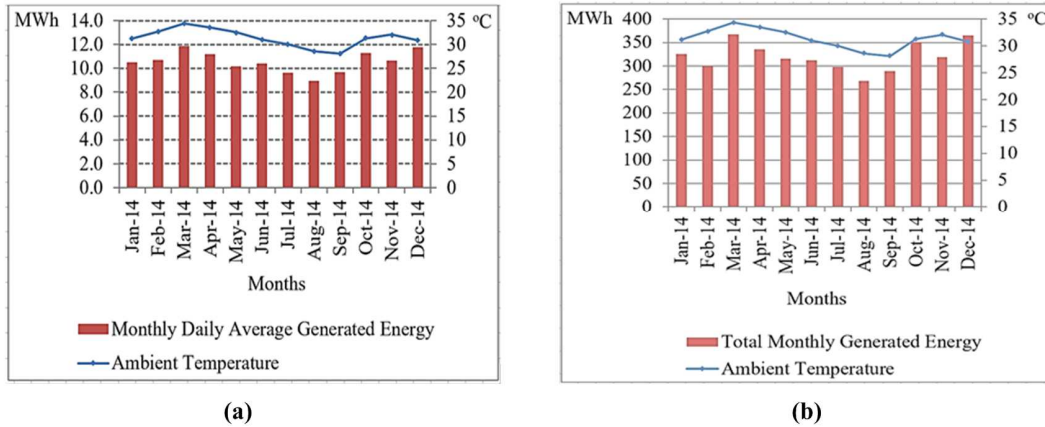


Figure 7. (a) Monthly Average Daily Generated Energy and Ambient Temperature; (b) Total Monthly Generated Energy and Ambient Temperature.

3.1.2. Results of PV Systems' Energy Output

The computed PV systems' monthly average daily and total generated energy influenced by global radiation as well as temperature variables over the evaluation period are presented in Figures 8(a) and 8(b).

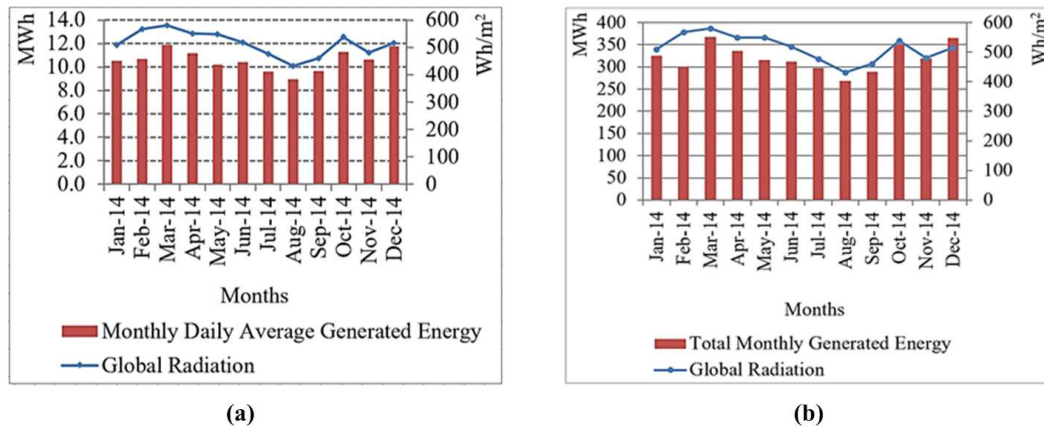


Figure 8. (a) Monthly Daily Average Generated Energy and Global Radiation; (b) Total Monthly Generated Energy and Global Radiation.

3.1.3. Results of the PV Systems' Yields

Figure 9 reveals the monthly average daily PV systems' reference, array and final yields over the evaluation period. The analysis is based on equations (3), (6), and (7) respectively.

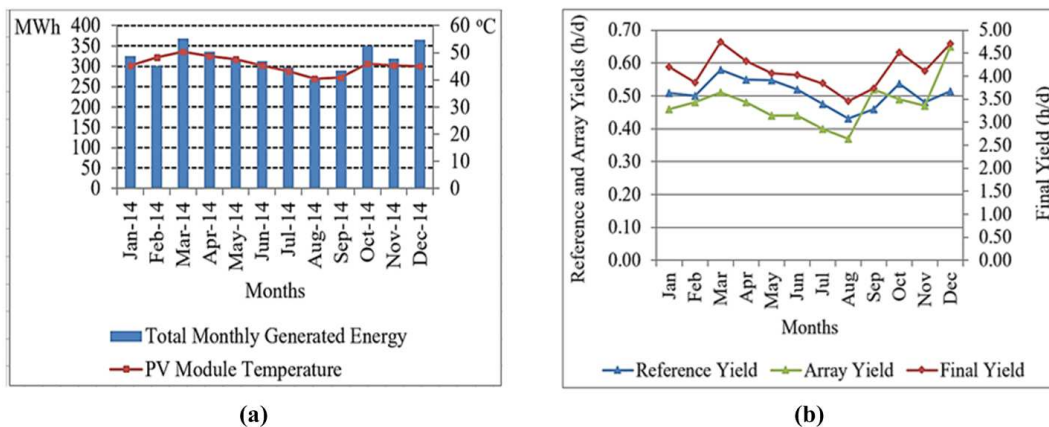


Figure 9. (a) Total Monthly Generated Energy and PV Module Temperature; (b) Monthly Average Daily PV Systems' Reference, Array and Final Yields.

3.1.4. Results of Monthly Generated Energy against PV Systems' Reference Yield and Performance Ratio (PR) Versus Capacity Factor (CF)

The computed total monthly generated energy during the evaluation period is graphed alongside the PV systems' reference

yield as shown in Figure 10(a). Monthly Average Daily PV Systems' PR and CF is also shown in Figure 10(b).

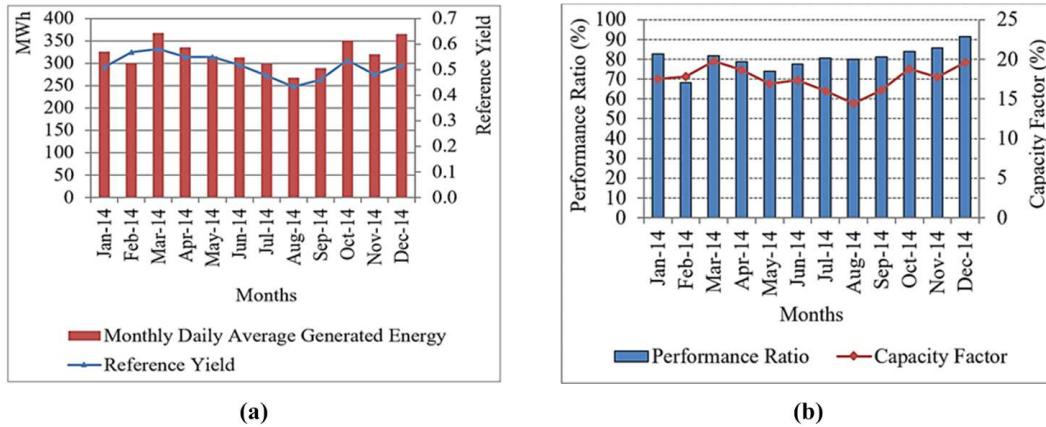


Figure 10. (a) Monthly Generated Energy and PV Systems' Reference Yield; (b) Monthly Average Daily PV Systems' PR and CF.

3.1.5. Results of PV Module, System and Inverter Efficiencies

Figure 11(a) shows the monthly average daily PV module and system efficiencies outcomes and that of the inverter efficiency is presented in Figure 11(b) during the evaluation period.

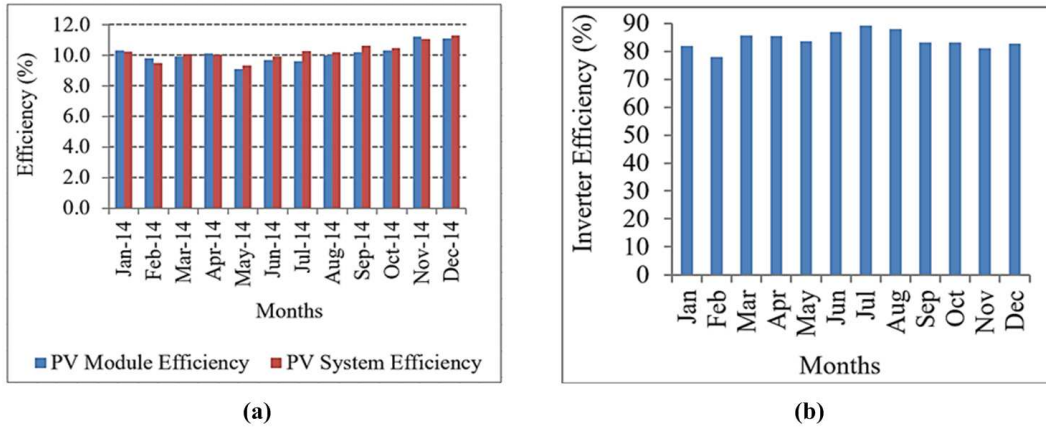


Figure 11. (a) Monthly Average Daily PV Module and System Efficiencies; (b) Monthly Average Daily Inverter Efficiency.

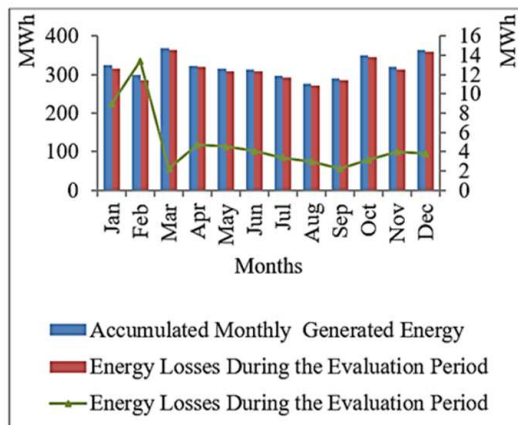


Figure 12. Accumulated Monthly Generated, Delivered and Energy Losses.

3.1.6. Results of Monthly Accumulated Generated and Delivered Energy with Corresponding Losses

The monthly accumulated generated and the energy delivered during the evaluation period is analysed and the

outcome depicted in Figure 12. The PV systems' energy loss on monthly bases over the 1-year period of evaluation is also presented.

3.2. Discussions

3.2.1. Ambient and PV Module Temperature Effect on the Monthly Generated Energy

As revealed in Figure 6(a), there was a corresponding trend that relates the varying effect of the monthly daily averaged ambient temperature to the PV module temperature values. The highest ambient temperature value of 34°C was measured in March and the highest PV modules temperature of 50°C occurred also, in March. The trend is almost the same for the minimum temperature values with a marginal percentage difference.

As can readily be seen in Figure 6(b), the degree of global radiation gave a corresponding increasing and decreasing effect on the PV modules temperature. March recorded the highest value of 580 Wh/m² of global radiation and PV modules temperature of 50°C. The minimum temperature

value of 40°C for the PV modules was realised where 432 Wh/m² of global radiation was noted. It can be seen from the trend that global radiation has proportionate effect on the PV modules temperature as observed by Kymakis *et al.* as well as Saleh *et al.* [8, 28].

For the plot of Monthly Average Daily Generated Energy (MADGE) and ambient temperature in Figure 7(a), the latter varied in a nearly oscillatory manner with 28°C and 34°C being the respective minimum and maximum values. Here, the minimum temperatures occurred in September while the maximum happened in March and April. On the other hand, the variation of MADGE still maintains its maximum and minimum values at March and August respectively.

The ambient temperature behaviour in Figure 7(a) repeats itself in Figure 7(b) with the total monthly generated energy (TMGE) ranging from a minimum value of 268 MWh in August to a maximum of 360 MWh in March. The PV modules temperature which is about 28% increment of the ambient temperature oscillates between 40°C and 50°C. The outcomes portrayed almost positive correlation behaviour between the output power and ambient temperature as observed by [29] as well as [30].

3.2.2. Effect of Global Radiation on Monthly Generated Energy

As revealed in Figure 8(a) the monthly daily average generated energy varied between 8.9 MWh and 11.9 MWh with March recording the maximum value. Additionally, the average global radiation varied from 432 Wh/m² to 580 Wh/m². In effect, the global radiation establishes a linear correlation with the corresponding generated energy. Similarly, March recorded the maximum total monthly generated energy of 360 MWh at 580 Wh/m² of global radiation whereas; August trailed at 268 MWh and 432 Wh/m² as depicted in Figure 8(b).

The above findings were corroborated by Mohammad *et al.* and several other related researchers that, at higher irradiance, PV cells produce higher output current leading to higher output power [31].

3.2.3. Monthly Average Daily PV Systems' Reference, Array and Final Yields

The monthly average daily reference and array yields during the evaluation period ranged from 0.43 to 0.58 h/d and 0.37 to 0.65 h/d in August and March respectively. The final yield varied from 3.46 h/d in August to 4.74 h/d in December. The annual average daily reference, array and final yields were 0.51 h/d, 0.48 h/d and 4.13 h/d respectively. Figure 9(a) shows the monthly average daily PV systems' reference, array and final yields over the evaluation period and Figure 9(b) revealing the graphical relation between Monthly Generated Energy and PV Systems' Reference Yield.

3.2.4. Monthly Average Daily PV Systems' Performance Ratio and Capacity Factor

From Figure 10(b), December attained the maximum PR of 91% while a minimum of 68% occurred in February. In effect, the PV Systems' PR values ranged from 68% to 91% with

annual average of 81%. In addition, March and December recorded the highest CF value of 20% while the lowest value of 14% occurred in August as portrayed in Figure 10(b). The CF therefore, ranged from 14% to 20% with an annual average of 18% during the evaluation period.

3.2.5. Monthly Daily Average PV Module, System and Inverter Efficiencies

With reference to Figure 11(a) and 11(b), the module efficiency ranged between 9.1% in May and 11.2% in November with an annual average daily efficiency of 10.1%. The PV Systems' efficiency on the other hand, varied between 9.3% in May and 11.3% in December with annual average daily value of 10.3%. Lastly, the monthly average daily Inverter efficiency varied from 78.0% in February as the minimum to a maximum of 89.2% in December with 84.0% as the annual daily value.

3.2.6. Accumulated Monthly Generated Energy, Delivered and Losses

The computed accumulated monthly generated and delivered energy over the evaluation period, as shown in Figure 12, revealed some considerable losses, especially in February. The accumulated generated energy ranged from 276 MWh in August to 368 MWh in March as the respective minimum and maximum values. Similarly, the minimum and maximum energy delivered occurred alongside the generated energy in August and March with variation from 272 MWh to 363 MWh. The annual accumulated generated and delivered energy is 3.84 GWh and 3.77 GWh, respectively.

Nearly 3% of the generated energy in January was lost and progressively increased to 4% in February. However, the trend took a positive turn when the losses were considerably reduced from 4% to 1% in March and to almost 0.2% in April. The losses from May to December nonetheless, were marginal at an average of 1%.

4. Conclusions

A performance study on the 2.5 MW peak grid connected solar photovoltaic power plant installed at Navrongo was evaluated on monthly daily average basis for 1-year. The following conclusions were drawn from the study:

- i) Monthly daily average generated energy is 10.7 MWh and the average total monthly generated energy is 320.5 MWh. Annual generated energy observed is 3845.8 MWh and total of 3768.0 MWh delivered to the grid;
- ii) Average energy lost is 4.7 MWh and annual energy lost is 56.2 MWh;
- iii) The annual average PR and CF is 81% and 18% respectively. PV modules and system efficiencies are 10.1% and 10.3% respectively;
- iv) The PV modules output power is largely influenced by the solar irradiation rather than the ambient, and module temperatures; and
- v) PV module output power increases at higher fill factor, thus ranging from 0.5 to 0.8 at higher solar irradiation.

5. Recommendations

The following recommendations are provided:

- i) Accumulation of dust on PV modules surface can significantly reduce the output power due to inefficient use of solar irradiation. Effective and efficient cleaning of PV modules surface is therefore, recommended in the solar PV power plant's operation and maintenance at Navrongo to practically achieve improved efficiency; and
- ii) Future work should consider the tilt angle of the mounted PV modules to ascertain it is at the appropriate angle to deliver optimum energy and possibly optimise the PV system by way of modelling and simulation.

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