TECHNO-ECONOMIC ASSESSMENT OF A 25 MW SOLAR PHOTOVOLTAIC SYSTEM FOR ELECTRICITY GENERATION IN EFFURUN-WARRI, NIGERIA

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Abstract: This paper was aimed at the techno-economic feasibility assessment of a 25 MW solar photovoltaic (PV) system for electricity generation in Effurun-Warri, Nigeria. The system advisor model (SAM) software was used to design and simulate the solar PV modules for power generation. Furthermore, the standard and validated models inbuilt in the SAM software were employed to analyze the techno-economic performance of the system and the energy losses. Results showed that the extent of energy losses considered in the design of the PV system had significant effects on system performance. For the 25 MW system assessed in this study, the highest monthly energy production was obtained at 3.9 GWh in January and the lowest at 1.9 GWh in July. Also, the total annual energy produced by the PV system was observed to depreciate as the system ages, with about 12% of the initial annual energy production expected to be lost after 25 years of system operation. The obtained capacity factor (12.1 %) and the performance ratio (0.75) revealed that the PV system in its current design would be inadequate to match the energy demand profile of Effurun-Warri, Nigeria. Additionally, the levelized cost of electricity (LCOE) was obtained as 0.65 cents/kWh for the system, which is about 85% higher than the current price of electrical energy in Southern Nigeria. Moreover, a negative net present value (NPV) was obtained for the plant, all indicating that the cost of investment would not be offset during the lifetime of the system, and the project would therefore not be profitable in its current design.

Keywords: solar photovoltaic (PV) system, renewable energy, solar energy, system advisor model (SAM), techno-economic analysis, sustainable energy feasibility assessment

1. INTRODUCTION

The modern world has witnessed a wave of population explosion in the last few decades, especially in developing countries [1]. The attendant consequences of this population explosion are conspicuous around the world today; including energy insecurity, an increase in emission of greenhouse gases, global warming, etc. To ameliorate some of these adverse effects on the human race, scientists have been working assiduously to develop energy and transportation systems that are fuelled by renewable and clean resources [2]. However, although such solar, wind, biomass, and other renewable energy and transportation systems are rapidly gaining traction in the developed world in terms of development and commercialization, little is yet to be desired of these systems in many developing countries. Among the causes of low application of renewable energy systems in these developing regions is the lack of technical and economic viabilities of such projects, due to low research funding and technical know-how. Thus, a lot of research funding and efforts are still required to massively develop

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renewable energy infrastructure in developing countries; and this has placed the current research effort in perspective.

Solar is among the most widely studied renewable energy sources worldwide, perhaps due to its universal availability at no cost [3, 4]. It can be harnessed using two main types of technologies; concentrated solar power (CSP) and photovoltaic (PV) systems. CSP systems employ tracking mechanisms to position a set of mirrors (collectors) in the direction of the sun, for the production of thermal energy in the receiver and subsequent conversion to electricity. In PV systems, however, panels track the photonic energy of the sun for direct conversion to electricity. Although the CSP systems are reported to have higher efficiency than the PV systems, the latter is much cheaper and requires much less land area, and that has made them more attractive for distributed energy applications [5]. Many researchers have applied different computer simulation methods to study the feasibilities and applications of PV systems for distributed energy generation in different countries; a summary of these studies is reported hereunder.

Granados et al. [6] assessed the feasibility of integrating solar PV systems into residential buildings in Colombia using system dynamics modeling. The authors reported that implementing such a scheme would reduce CO_2 emissions of the residential sector in some key cities by about 2600 – 7200 tons by the year 2050. Iqbal et al. [7] developed and assessed a grid-connected PV system with a battery for integration into the energy system of a University campus in Pakistan. The authors reported that the hybrid solar energy scheme would reduce energy costs by about Rs. 0.251/kWh. Imasiku [8] employed the System Advisor Model (SAM) software to model the technical and economic feasibility of deploying PV systems for powering grid-connected buildings in Zambia. He reported that a 1 kW PV system modeled for 5 years of operation would achieve investment payback in 3 years with about a 69 % performance ratio; meaning that the project is feasible in Zambia. Kavuma et al. [9] analyzed the viability of grid-integrated PV systems in Uganda based on the SAM simulation program. They reported the possibility of annual energy generation of about 70 GWh, with between 13.1 % and 17.5 % capacity, and a positive net present value (NPV), all of which favour investment in a PV system in the country. Gul et al. [10] developed a mathematical model to maximize power generation from a PV system and its balancing to match demand from a university campus and neighboring communities. The DC storage integrated system, modeled using the SAM software, was reported to produce about 2.8 GWh of electricity in its first year of operation, with a levelized cost of electricity (LCOE) of about 4 cents$/kWh. Mirzania et al. [11] equally applied the SAM software to assess the techno-economic feasibility of a battery integrated PV system in the UK without the usual feed-in-tariff (FIT) from the Government. The authors developed a business model and using it to analyze different scenarios, concluded that it would be possible to completely offset the cost of PV-battery projects in the communities and make a profit, even in the absence of subsidies from the Government. Da Silva and Branco [12] applied SAM software to compare the techno-economic feasibilities of PV systems with and without energy storage (battery) in the city of Belem, Brazil. They reported that the PV system without a battery outperformed the battery integrated one both in technical and economic terms. Dujardin et al. [13] studied the techno-economic optimization potentials of PV systems in the Alpines and reported that, with adequate placement, both the energy production and economic performance can be significantly improved in this region. Vrinceanu et al. [14] studied the current investment trend of PV systems in Romania and proposed suitable sites for solar PV farms in the country. Miravet-Sánchez et al. [15] studied the impacts of PV installations as replacements for traditional fossil-fuelled energy systems among the Latin and Caribean Americans. They reported generally that PV information would improve the health and general well-being of the inhabitants of this region; and specifically that about 2165 tons/year of CO2 can be prevented by installing PV systems in just 9 communities within the region, among other benefits. Benti et al. [16] demonstrated the techno-economic feasibility of solar PV systems for rural electrification in Ethiopia, using as case studies the energy demands of schools. Additionally, Agyekum [17] applied the SAM software to compare the technical and economic performance of PV systems with and without storage devices for three different climatic regions of Ghana. The author reported that the tracking mechanism adopted has significant impacts on performance, with the lowest LCOE reported as 5-6 cents/kWh for the single and double axis tracking mechanisms in the Northern climate region. Also, Imam et al. [18] reported that grid-connected PV installation in a typical residential building in Saudi Arabia is feasible, based on several techno-economic indices obtained from the SAM software. Furthermore, other authors affirmed the technical and economic feasibilities of rooftop solar PV designs [19–22] and floating PV designs [23, 24] for specific locations around the globe.

The literature review in the foregoing clearly shows that solar projects based on PV technology are becoming competitive, albeit depending on the location. Also, it is explicitly revealed in the review that SAM is a very vital and popular tool being used for the design and simulation of solar PV systems, perhaps because it is opensource software and its ability to account for the dynamic nature of climatic parameters up to minute-by-minute variation in the simulation. While feasibility studies have been carried out for different countries of the world, information is non-existent on the techno-economic feasibility of large-scale PV systems for electricity generation in Nigeria, despite its climatic potential. To bridge this gap, this study aims to apply the SAM software to assess the viability of a 25 MW PV plant for the climatic condition of Effurun-Warri, Southern Nigeria. The specific objectives of the study are:

- To size the solar panels and other components of a 25 MW solar PV system using the SAM software and first principle design calculations;
- To analyze the yearly energy production profile of the 25 MW PV system based on the ambient conditions of the twin city of Effurun-Warri in Southern Nigeria; and
- To assess the economic feasibility of the 25 MW PV system based on the current market realities in Nigeria.

The methodology adopted in this paper is presented in section 2, the results and discussion in section 3, while the main conclusions are highlighted in section 4.

2. METHODOLOGY

2.1. Plant scheme and meteorological data

The 25 MW solar PV system designed in this study follows the general/standard principles already established in the literature for this type of system. It consists of an array of solar panels which collect thermal energy directly from the sun. Other key units of the system are the combiner box (to unify energy from the different panels), direct current (DC) and alternating current (AC) termination switches (to control the flow of currents), inverter (to convert DC to AC) and AC breaker panel (to isolate the flow of alternating current), etc. It is assumed that the PV system is grid-connected, and the schematic arrangement provided in [25] succinctly illustrates the reference system in this study, as shown in Figure 1.

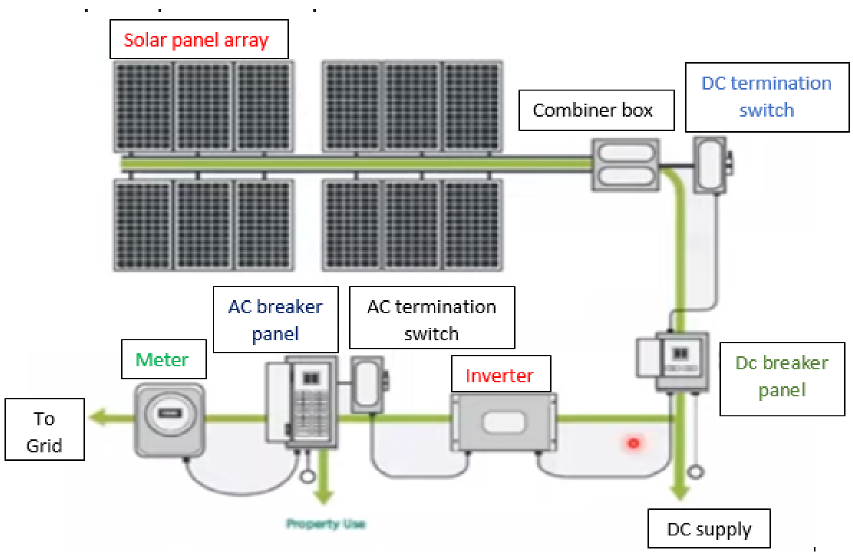

Fig. 1. PV system components and operational arrangement.

The meteorological parameters of Uvwie Local Government Area of Delta State, where Effurun-Warri is located, were fetched from the National Solar Radiation Database (NSRDB), as highlighted in Table 1. They validate the inbuilt data generated by the SAM software for this location.

Table 1. Meteorological parameters of Effurun-Warri, Nigeria.

Parameter	Value
Latitude (°)	5.57
Longitude (°)	5.78
Tilt angle (°)	20
Azimuth angle (°)	180

Average temperature (ºC)	25.9
Global Horizontal Irradiation (GHI) ($kWh/m^2/day$)	3.39
Average wind speed (m/s)	0.4

2.2. Modeling and simulation of the 25 MW PV system

A first-principle calculation model was applied to determine the total inverted energy (IE) required of the PV system, as follows:

$$IE = \frac{NP * GHI * \gamma}{\varphi} \tag{1}$$

Where NP is the nominal power of the PV system (25 MW), GHI is the global horizontal irradiation of the plant location, γ is the energy loss factor on the panels (taken as 0.3 in this study) and φ is the inverted power efficiency (taken as 0.95 in this study). Then, the System Advisor Model tool was employed for detailed modeling and simulation of the PV system. In the SAM tool, the PV system was set up for performance modeling through the selection of a DC inverter side configuration and by configuring it to the location of the plant to obtain climatic parameters corresponding to those listed above. Next, solar panel and inverter types were specified, followed by the specification of a battery storage type and PV module cost. Two different case studies were carried out for the design of the PV system in the SAM software, based on the value of IE given in equation 1. Case 1 took into account the projected energy loss before the sizing of the system components, assuming that γ = 0.3. In case 2, this loss was not considered for the system design, thereby taking γ as 1 in equation (1).

Furthermore, a financial model was set up in the SAM software to calculate the cash flow and economic metrics of the PV project over its lifetime. The levelized cost of electricity (LCOE), the net present value (NPV), and other associated metrics were employed for the economic analysis of the PV plant, while the total energy produced, annual energy yield, capacity factor, and performance ratio were used for the technical assessment of the plant. All these techno-economic metrics are inbuilt into the SAM software, and the different definitions and source models are available in [9, 25].

3. RESULTS AND DISCUSSION

3.1. System Advisor Model (SAM) design parameters of the PV system

The basic design parameters obtained from the SAM software are highlighted in Table 2 for the two case studies. As would be expected, designing the PV system without adequate consideration for the irradiation and ancillary losses would lead to under-design. Specifically here, the number of PV modules obtained from the design was lower by about 18 % when the irradiation losses were not considered (case 2), relative to case 1. Similarly, about 1200 more inverters are required for the PV system based on the design the case as compared to that in case 2. The under-design in case 2 is further reflected in the land area required for the project and its projected cost, with case 1 requiring an extra 25,838 m^2 of land and \$6,244,720 when compared with case 2.

Table 2. Design parameters of the PV system for two different case studies.

Variables	Case 1 – designing with energy loss consideration	Case 2 – designing without the energy loss considerations
Number of modules	88,175	72,476
Number of inverters	6,198	5,000
Energy in DC	30,938.7 kW	20,833 kW
Inverted Energy in AC	25,597 kW	20,833 kW
Area	144,046.4 m^2	118,208.4 m^2
Cost of the Plant	\$ 32,534,404	\$ 26,289,684

3.2. Techno-economic simulation results

The trend of energy produced by the PV system in each month of a typical year is illustrated in Figure 2. As can be seen, the highest monthly energy of about 3.9 GWh is produced by the PV system in January and the lowest of about 1.9 GWh in July. However, the simulation also revealed that the annual energy generated from the PV system is expected to decrease with the increasing life of the plant. The trend of the annual energy depreciation can be seen in Figure 3, where the annual energy after 25 years of the plant operation would have reduced by about 12%. The reduction is due principally to the depreciation in the system performance due to soiling and other losses. The SAM software took into account a lot of these ancillary losses during design, and a selected few are presented here in Figure 4 based on the nominal point of array (POA), in Figure 5 based on the net DC energy produced, and in Figure 6 based on the gross AC energy.

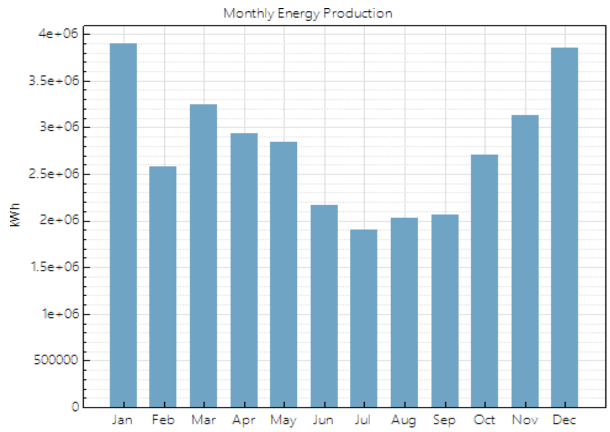

Fig. 2. Monthly energy production of the PV system in the first year of operation.

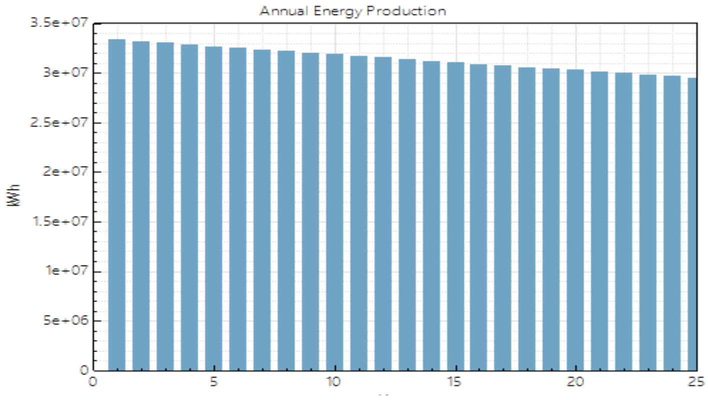

Fig. 3. Yearly energy production over the plant life.

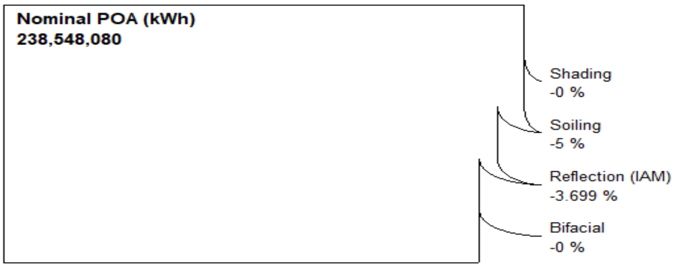

Fig. 4. Percentage of energy loses at Nominal POA (KWh).

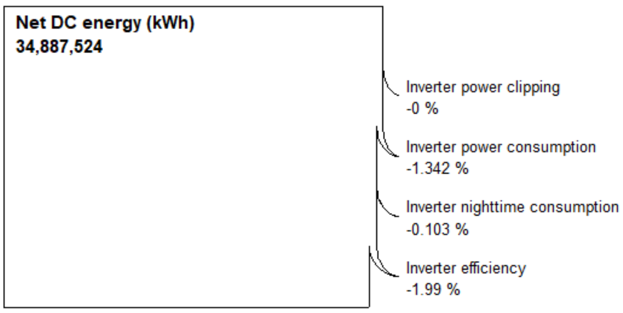

Fig. 5. Percentage and types of losses per the net DC energy generated (KWh).

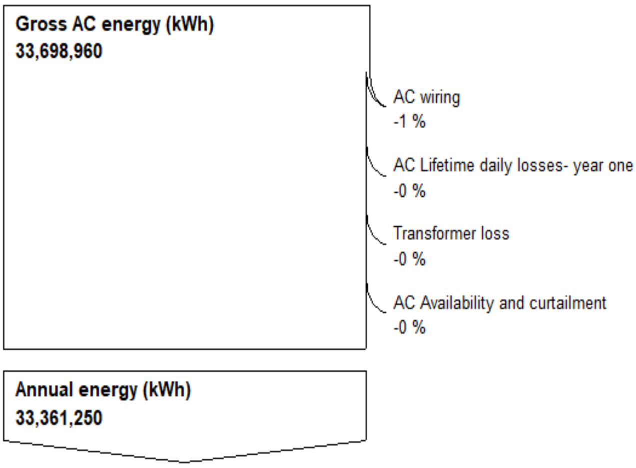

Fig. 6. Percentage and types of losses per the gross AC energy generated (KWh).

The techno-economic performance metrics obtained for the 25 MW PV system at Effurun-Warri, Nigeria are summarized in Table 3. The capacity factor and performance ratio were obtained as 12.1 % and 0.75 respectively, indicating that the PV system is not able to match adequately with the energy demand of this city. Furthermore, the LCOE of 0.65 cents/kWh was obtained, which is higher than the cost of electricity obtainable in this part of Nigeria (about 0.10 cents/kWh) by almost 85 %. Additionally, a negative NPV was obtained for the proposed project, meaning that the investment cost would not be completely offset in the lifetime of the system, thereby generating losses for investors.

Table 3. Techno-economic performance metrics of the PV system.

Metric	Value
Annual energy (year 1)	32.67 GWh
Capacity factor (year 1)	12.1%
Energy yield (year 1)	1,056 kWh/kW
Performance ratio (year 1)	0.75
Levelized COE (nominal)	1.61 cent$/kWh
Levelized COE (real)	0.65 cent$/kWh
Net capital cost	$50,583,128
Net present value	$-2,107,600

4. CONCLUSIONS

The techno-economic feasibility assessment of a 25 MW solar PV system was designed and simulated as a potential electricity generation source for the twin city of Effurun-Warri, Nigeria. The design and simulation were achieved using the System Advisor Model (SAM) software and based on the meteorological data of the reference Nigerian city. The main study conclusions are:

- Neglecting solar energy losses in sizing the main components of a PV system would result in gross under-design;
- The highest monthly energy of about 3.9 GWh is produced by the PV system in January and the lowest of about 1.9 GWh in July, with the annual production reducing significantly by about 12% of 25 years assume das the life of the plant;
- The capacity factor and performance ratio of 12.1% and 0.75 respectively were obtained, and the LCOE of 0.65 cents/kWh, compared to about 0.10 cents/kWh cost of energy in Nigeria at the moment, with a negative NPV which suggests an unprofitable investment.

It is recommended that a comparative techno-economic study of PV projects in Nigeria should be carried out considering several climatic regions of the country. Additionally, a lower PV nominal power should be considered for such a detailed comparative analysis.

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