International Journal of Scientific & Engineering Research Volume 12, Issue 8, August-2021
ISSN 2229-5518

Techno-economic analysis of a grid-connected solar PV for a University Departmental Building in Enugu, Nigeria

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Abstract—Electricity access duration and reliability in Nigeria is poor. This makes the various departments in the Enugu State University of Science and Technology (ESUT) campus resort to the use of petrol generators to supplement facility loads. Noise, environmental pollution and energy sustainability are the main worries. To abate these concerns, the Nigerian government is encouraging the maximum deployment of renewable energy resources for power generation. Solar resources are available at moderate levels in Enugu and can be tapped to supply the ESUT campus with its supplementary energy requirements. In this paper, the technical and economic potential of supplying the electric load of the faculty of engineering building housing mechanical and electrical departments with 2-axis solar photovoltaic based electricity is investigated. It is found that it is technically and economically feasible to supply the building with all its electricity needs using a 60 kW 2-axis solar PV system. Annual output of 115 MWh at a capacity factor of about 22% is observed. At a discount rate of 15%, the NPV of the system is estimated $19,978 with a simple payback period of about 11.1 years and a cost of electricity of 0.184 $/kWh. Sensitivity analyses revealed that the key parameters that considerably affect the profitability of the PV system for the campus are the total initial costs, electricity export rate, and energy produced by the system.

Index Terms— COE, Economic Analysis, NPV, Renewable Energy, Solar PV, Solar module, Inverter

1 Introduction

Availability and access to reliable, safe, affordable and efficient electricity is a vital prerequisite for overcoming poverty, stimulating economic and human development in both rural and urban areas. It is also an essential input for advancing education, health, research and access to other infrastructure services.

Regrettably, despite the availability of enormous natural energy resources in Nigeria, the country suffers from acute electricity shortage and duration problems, which is deterring its development.

According to the World Bank [1], 85 million out of about 200 million Nigerian population do not have grid access. Those with grid access experience an unreliable and epileptic service, mostly below their demand. This is because of an obsolete generation infrastructure that can generate only 32% (4 GW) of its potential (12,522 MW), an overburdened grid that only delivers about 25% of installed capacity to end-users and a transmission system of 8,100 MW capacity but with all-time transmission peak of 5,459MW [2].

The energy deficiency in Nigeria leads to poor electricity access and duration in almost all Nigeria Universities leading to unnecessary difficulties in learning and research. To supplement the grid power shortage in the Nations institutions, most Universities resort to the use of costly and pollution prone diesel/petrol power generating sets to meet their power needs and expectedly, this exacts a massive cost on the institutions' insufficient resources, accompa nied by the hazards posed by unsafe emissions.

Renewable energy (RE) resources such as wind, biomass, small hydro and solar radiation are abundant in Nigeria with high estimates of technical potentials for power generation as shown in Fig. 1 [3].

Thus RE could be deployed to bridge the energy supply and demand gap in the country, including providing supplementary power to facility loads in the nation's institutions of learning.

Among the RE sources, power generation from solar is projected to play a notable role in improving power supply sustainably in the country. This is on account of Nigeria's strategic geographical position that makes it possible to capture a huge quantity of solar radiation that is properly distributed; varying from 1534 - 2264 $kWh/m^2/year$, averaging 19.8 MJm^2/day with over 6.5 sunshine hours per day [4].

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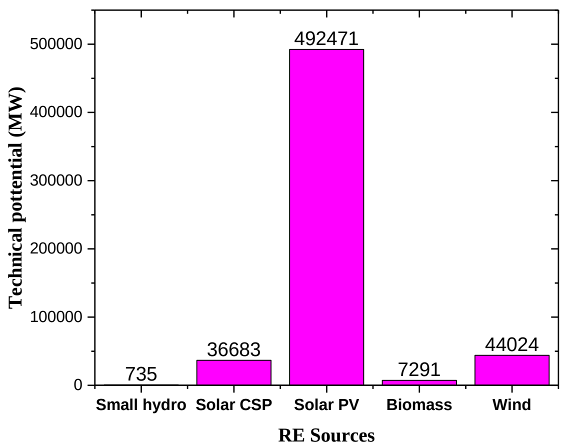

Fig. 1. Technical potential of RE sources in Nigeria for power generation

Globally, solar photovoltaic (PV) has become an attractive and stand out alternative for supplying power to schools because of the increasing technological improvements, declining cost of solar PV and most importantly, most schools have large, flat rooftops that are suited for rooftop solar PV or solar thermal systems. Furthermore, school facilities often have car parking areas that could be put to productive use by mounting solar PV canopies that harness the sun's power and deliver the extra advantage of providing shades for parked vehicles on sunlit days.

In Nigeria, however, it has been recognised that the main obstacles to the development and deployment of solar RE resources include the insufficient level of support for R&D on local solar potentials, lack of access to capital and lack of appropriate legal and policy frameworks [5].

Given that the technical output profile from solar and other RE based power systems is site-specific and depends on factors such as; the installation's site and its related weather and meteorological conditions, it is imperative to properly carry out a site-specific evaluation based on the specific local meteorological conditions to examine the related costs, size of the component and overall economics while ensuring the reliability of power from such RE systems. Also, the investors' disposition to commit capital to solar and other RE projects are chiefly driven by the overall economics and risk-return profiles of such investments [6]. In this context, the key objective of this study is to examine the technical and economic viability of executing a grid-connected solar PV system at the Mechanical and Electrical Engineering Departmental Building at the Faculty of Engineering, Enugu State University of Science and Technology (ESUT), Enugu Nigeria hereafter referred to as the departmental building. The current research seeks to add to the existing research in the solar RE sector in Nigeria and will help expedite the growth and deployment of solar RE in the country.

2 METHODOLOGY

The system was modelled in RETScreen® software. The Methodology adopted to perform the techno-economic analysis of the Solar PV plant is a multi-phase approach consisting of site description and resource assessment, Electricity load estimation, sizing the PV system, financial, sensitivity and environmental analysis.

2.1 Site description

Mechanical and electrical engineering building of the Faculty of Engineering ESUT campus located at Agabni, Enugu state Nigeria is the site of study. The geographical coordinates of the site are 6.3° N, 7.5° E and 108 meters above sea level. The building consists of two floors with classrooms, offices for academic and administrative staff, stores and toilets. The proposed PV system will be mounted on the rooftop of the building and there are not any obstacles that could obstruct the panels. Table.1 shows the variation of climatic parameters in the site. The solar radiation in the site varies from a min of 3.91 to a maximum of 5.74 with average solar irradiation of 4.92 kWh/m²/day.

TABLE 1

CLIMATIC PARAMETERS

Month	Air Temperature (°C)	Daily solar radiation horizontal (kWh/m2/d)
Jan	24.0	5.68
Feb	25.7	5.74
Mar	26.6	5.57
Apr	26.6	5.25
May	26.2	4.94
Jun	25.3	4.54
Jul	24.6	4.13
Aug	24.6	3.91
Sep	24.8	4.19
Oct	25.0	4.57
Nov	25.3	5.11
Dec	23.9	5.46
Annual	**25.2**	**4.92**

2.2 Load estimation

The electric load is the total power and energy consumption of all appliances in the building that need to be supplied by the solar PV system. The peak electrical load requirement of the spaces in the building was estimated by summing up the product of each the wattage rating of every appliance in the space with the duration of use in a day. Then the total load of the building was obtained by summing up the individual load of each space. A peak load estimation of 143,778 Wh/day is obtained. Thus the yearly energy bill cost in this facility is about

N 2.4 million ($5,855) at national special commercial energy tariff for universities of 45.26 Naira/kWh [0.11 $/kWh] [7]. Table.2 summarises the details of the calculation of this load.

2.3 Sizing the PV system

The sizing of a grid-connected PV system without battery storage involves principally the determination of the load to be met, selection of PV modules and an appropriate inverter to meet the load [8].

The total load (Watt-hours per day) which must be provided by the panels is obtained as follows:

$$\text{Total load} = \text{total appliance load} + \text{safety load} \quad (1)$$

In the research, a safety load of 30% of total appliance use is assumed. The total Watt-peak rating (Wp) needed for PV modules is obtained using the following equation:

$$W_p = \frac{\text{Total load}}{\text{Panel generation factor}} \quad (2)$$

A panel generation factor of 3.41 is used [9]. Thus the total Watt-peak rating which must be provided by the panels is approximately 60 kW.

The number of PV panels for the system is obtained as follows:

$$\text{number of modules} = \frac{W_p}{W_p^r} \quad (3)$$

Where W_p^r the rated PV power rating of modules available. Tables 3 shows the characteristics of the PV module selected. A two-axis tracking PV system has been considered in the analysis.

TABLE 2
LOAD EVALUATION OF THE DEPARTMENTAL BUILDING

S/N	Section	Appliances	Qty	Rating Watts (W)	Usage interval	Usage (hr/d)	AC load (Wh/d)	Total category load/day (Wh/d)
1	2 Unit Head Offices	Bulbs.	4	20	8am-4pm	8	640	
		Ceiling fan.	2	120	8am – 4p	8	1920	
		Laptop.	2	65	12pm-4pm	4	520	
		Air conditioner.	2	750		5	7500	
		Printer.	2	500		4	4000	
		Desktop computer.	2	250		4	2000	
		Photocopier	2	950		3	5700	
		TV set.	2	80		8	1280	**27,848**
		TV decoder.	2	18		8	288	
		Refrigerator	2	250	8am-4pm	8	4000	
2	15 Offices	Bulbs.	30	20	8am-4pm	8	4800	
		Ceiling fan.	15	120		8	14400	
		Laptop.	30	65		4	7800	
		Air conditioner.	15	750		5	56250	**83,250**
3	5 Lecture halls	Ceiling fan.	20	120	8am-4pm	8	19200	
		Bulbs	30	20		8	4800	
								24,000
4	2 Stairways	Bulbs	12	20	7am-5pm	9	2160	**2160**
5	12 Convenience	Bulbs	12	20	8am-5pm	4	960	**960**
6	6 Pathways	Bulbs	20	20	8am-5pm	9	3600	**3600**
7	Outside lights	Bulbs	7	20	6pm-7am	14	1960	**1960**
	Total appliance load (Wh/day)							**143,778**

Based on the meteorological parameters of the university campus as in (Table 1), the hourly energy provided by the PV modules can be calculated using the following equation [10]:

$$E_{grid} = \eta_{inv}\eta_p H_t A_r \times (1-\gamma_r) \times (1-\gamma_{pc}) \quad (4)$$

Where η_{inv} is the efficiency of the inverter, (η_p) is the average array efficiency, A_r is the area of the array, H_t is hourly irradiance in the plane of the PV array and γ_r *and* γ_{pc} are PV array losses and other power conditioning losses respectively.
The average efficiency of the array (η_p) is calculated from the average module temperature T_c as follows:

$$\eta_p = \eta_r\left[1-\beta_p(T_c-T_r)\right] \quad (5)$$

Where η_r is the PV efficiency of the module at a reference temperature T_r, β_p is the temperature coefficient. The average module temperature T_c is calculated from the average monthly ambient temperature T_{amb} as follows:

$$T_C = T_{amb} + (219 + 832K_t) \times (NOCT - 20)/200 \quad (6)$$

Where K_t is the monthly clearness index *and NOCT* is the Nominal Operating Cell Temperature.

Inverters are very indispensable devices for PV systems connected to the grid; they convert the DC power produced by the PV arrays into AC power. For on-grid systems, inverters likewise ensure safety by detecting variability on the grid and shutting down. Therefore, it is important to have high inverter efficiency. The input inverter capacity rating in this study is set equal to the PV array rating to ensure safe and efficient operation [10].

TABLE 3

CHARATERISTICS OF THE PV SYSTEM

Photovoltaic	
Type	Mono-Si
Manufacturer	China Sunergy
Model	Mono-Si – CSUN200-72M
Number of units	300
Efficiency	15.67%
Nominal operating cell temperature	45 °C
Temperature coefficient	0.4%
Solar collector area	383 m²
Miscellaneous losses	4%

2.4 Technical analysis

The technical performance of the PV system for the faculty building was analysed in terms of energy yield, (EY), capacity factor (CF), specific yield (SY) and carbon dioxide emission reduction (CDER).

2.4.1 Specific Yield

Specific Yield (SY) is one of the frequently deployed performance metrics for a solar system. It reveals how much energy (KWh) will be produced for every KWp of solar modules installed. In the paper, SY is calculated as follows;

$$SY = \text{plant output (kWh)}/W_p^r\text{ (kWp)} \quad (7)$$

2.4.2 Capacity Factor

The Capacitor Factor (CF) of a PV plant is the ratio of the actual output (KWh) and the rated plant output, assuming the plant operates at nominal capacity the whole year.

$$CF = \text{plant output (kWh)}/(8760\text{ hours} \times W_p^r\text{ (kWp)}) \quad (8)$$

2.5 Financial analysis

The economic performance of the system was analysed using common metrics deployed in the analysis of energy projects. They include net present value (NPV), Cost of electricity (COE) internal rate of return (IRR) and the payback time (PBT). The NPV can be calculated using the following formula [11]:

$$NPV = \sum_{n=0}^{N} \frac{\hat{C}_n}{(1+r)^n} = -TIC + \sum_{n=1}^{N} \frac{\hat{C}_n}{(1+r)^n} \quad (9)$$

Where TIC is the total initial cost, N is project duration, n is the analysis year, r is the discount rate, Ĉ is the after-tax cash flow (Revenue –cost) which comprise capital outlays (CAPEX), operational outflow (OPEX), loan financing, incentives (if applicable) and taxes.

The internal rate of return (IRR) is the discount rate (r) that makes the NPV become zero. IRR can be determined by solving the following equation iteratively:

$$NPV = -TIC + \sum_{n=1}^{N} \frac{\hat{C}_n}{(1+IRR)^n} = 0 \quad (10)$$

The cost of energy (COE) is the minimum cost at which the produced electricity from the PV plant must be sold over its lifetime to break even. It can be obtained by solving the ratio of total life cycle cost (TLCC) and electricity generated (EG) annually as follows [12] :

$$COE = \frac{TIC + \sum_{n=1}^{N} \frac{C_{R,n} + C_{O\&M,n}}{(1+r)^n}}{\frac{GE_n}{(1+r)^n}} \quad (11)$$

Where $C_{R,n}$ and $C_{O\&M,n}$ are the replacement cost and operation and maintenance cost and GE_n is the generated electricity at year, n respectively. Table 4 shows the financial parameters of the system. The specific cost and operation and maintenance (O&M) cost of the PV system is taken from the RETScreen® cost database as 1800 $/kWh and 30 $/kW-year respectively [13]. Inverter replacement cost is taken as 5% of total initial cost (TIC) and occurs at the 13th year.

TABLE 4
FINANCIAL PARAMETERS

Inflation rate	**10%**	**Debt interest rate**	**13%**
Discount rate	15%	Debt term	15 years
Project life	25 years	Depreciation method	Straight line
Debt ratio	70%	Depreciation period	15 years
Tax rate	30%	Electricity export rate	0.10 $/kWh

3 RESULT AND DISCUSIONS

3.1 Technical results

The data obtained from RETScreen® software which is based on NASA Surface Meteorology measurements [13] shows that the entire location of the Engineering building experiences an average daily solar radiation on a horizontal surface of 1796 kWh/m²/year through the year. The monthly average solar radiation on a horizontal surface varies from 3.91 kWh/m²/day in August to 5.74 kWh/m²/day in February, with a mean of 4.92 kWh/m²/day. Based on the solar resource in the site, the monthly power exported to the grid by the PV system in a year is shown in Fig. 2.

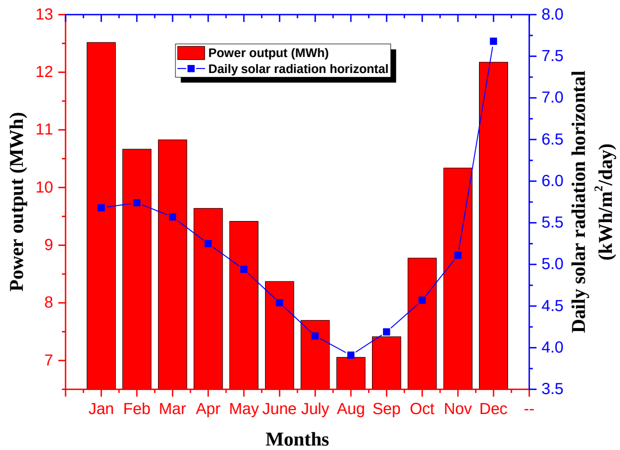

Fig. 2. Monthly average power output

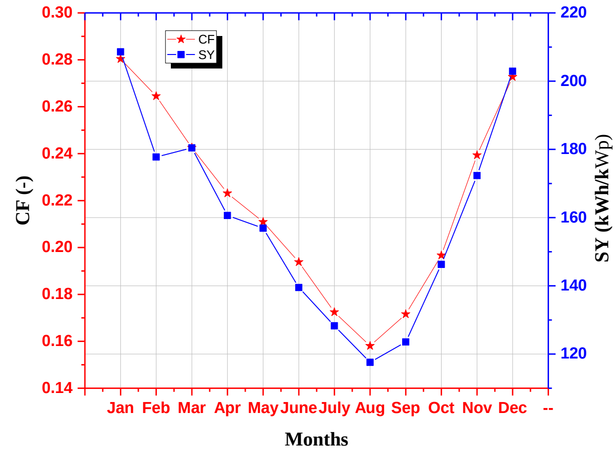

Fig. 3. Monthly capacity factor (CF) and specific yield (SY)

It can be seen from Fig. 2 that the power output varies according to the prevailing meteorological parameters of the site for a given month, with a maximum output of 12.52 MWh occurring in January and a minimum output of 7.06 MWh occurring in August. The overall power generated by the system in a year for the site is 115 MWh with an average monthly energy production of 9.57 MWh at a capacity factor (CF) of 21.9%. The annual energy produced by the system is more than the peak yearly energy demand of the faculty building estimated at 52.48 MWh. Based on the yearly energy bill cost in this facility of about N 2.4 million ($5,855), our analysis suggests that roughly $6,250 (N 2,561,750.00) excess electricity sales revenue could be made annually if a PV system is installed in the departmental building.

The monthly CF varies from a minimum of 15.8% % in August to 28.0% in January, as shown in Fig. 3. Based on the monthly average CF of 21.9%, the two-axis PV system analysed in this research can be said to generate rated power in about 1918 h or about 80 days in a year. The annual specific yield (SY) of the system for the site is 1916.7 kWh/kWp. This means that the PV system has to operate for about 1917 hours at its installed capacity to produce the generated annual energy.

At a greenhouse gas (GHG) emission factor of 0.433 tCO_2/MWh and 19% transmission and distribution (T&D) losses, the gross annual reduction in GHG emissions estimated to occur if the proposed PV system is realized is estimated as 49.7 tonnes of CO_2 emissions per year (tCO_2/yr) or 81% reduction in CO_2 from the base case. This is equivalent to 115.6 barrels of crude oil not consumed or 21,354.3 litres of gasoline not consumed.

3.1 Financial results

The financial results of the PV system are summarised in Table 5. The total yearly costs required to operate, maintain and finance the proposed 2-axis tracking PV system using a mono-Si PV system is estimated at $ 13,492. Based on this, the costs of electricity (COE) produced by the system is estimated as 0.184 $/kWh which is higher than both the set feed-tariff of 0.10 $/kWh and the national special commercial energy tariff for universities of 45.26 Naira/kWh (0.11 $/kWh) [7]. However, as can be seen from Table 5, the implementation of the system is financially viable with a positive Net Present Value (NPV) of $ 19,978. The equity payback time or the length of time required for the system to recoup its total initial equity cost, out of the revenue or savings it generates is 9 years.

TABLE 5
FINANCIAL RESULTS

Indicator	*Value*
Simple payback	11.1 years
Equity payback	8.9 years
NPV	$19,978
COE	0.184 $/kWh
Benefit-cost ratio	1.6
Annual life cycle savings	$3,091

3.2.1 Sensitivity analysisn

Under the sensitivity analysis, the sensitivity of uncertainty in key financial parameters on the NPV is estimated. The parameters considered are total initial cost (TIC), operation and maintenance (O&M) cost and electricity export rate (EER). The impact graph of NPV presented in Fig. 4 shows the relative contribution of the uncertainty in each key parameter to the variability of NPV.

It can be observed from Fig. 4 that the two key economic parameters that greatly influence the project outcome financially are the total initial costs (TIC) and electricity export rate (ERR). The impact of simultaneous variation in EER and TIC by ± 30% on the NPV is depicted in Table 6. As can be seen, the profitability of the system increases with rising EER and decreasing TIC. Under the base case electricity export rate of 0.10 $/kWh, the profitability of the investment is protected for up to 20% increases in TIC. Also, the profitability of the project is protected up to an EER reduction of 10%.

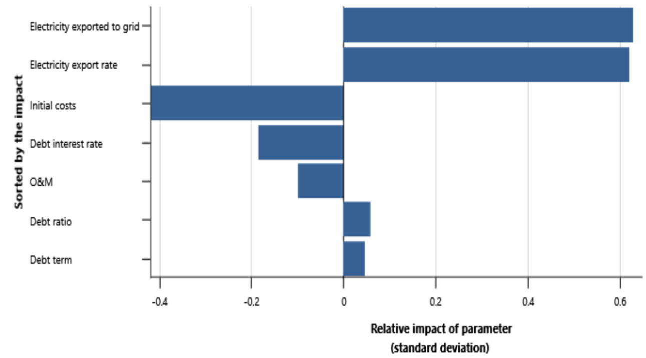

Fig. 4. Impact graph of NPV

TABLE 6
FINANCIAL RESULTS

Sensitivity analysis

Perform analysis on: Net Present Value (NPV)
Sensitivity range: 30%
Threshold: 0 $

- Remove analysis

Electricity export rate ($/MWh)		Initial costs ($) 75,558 -30.0%	86,352 -20.0%	97,146 -10.0%	107,940 0.0%	118,734 10.0%	129,528 20.0%	140,322 30.0%
70.00	-30.0%	6,833	-2,462	-11,940	-21,545	-31,234	-40,991	-50,827
80.00	-20.0%	20,285	11,280	2,048	-7,346	-16,851	-26,490	-36,185
90.00	-10.0%	33,222	24,585	15,672	6,557	-2,768	-12,248	-21,796
100.00	0.0%	45,773	37,478	28,851	**19,978**	10,904	1,652	-7,692
110.00	10.0%	57,974	50,053	41,734	33,118	24,280	15,210	6,022
120.00	20.0%	69,844	62,322	54,332	45,990	37,385	28,546	19,516
130.00	30.0%	81,714	74,303	66,666	58,612	50,245	41,651	32,813

+ Add analysis

5 CONCLUSION

In this research, the technical and economic potential to meet the electrical load of the faculty of engineering building housing Mechanical and Electrical Engineering Departments in Enugu State University of Science and Technology (ESUT) with a grid-connected roof-top solar photovoltaic (PV) based electricity is analysed. The following conclusion can be drawn:

- It is technically and financially feasible to meet the load of the faculty of engineering building with a two-axis tracking PV system capacity of 60 kW consisting of 200 Mono-crystalline silicon modules of 200 Wp of nominal power rating per module, at an efficiency of 15.67% and 1.277 m^2 total module area.
- The mean annual energy exported by the PV system is 115 MWh at a capacity factor of about 21% with a maximum energy output of about 12.52 MWh in January and a minimum output of about 7.05 MWh in August.
- The determined economic outcome of the study points out a net present value of $19,978 with an 18.9% internal rate of return on equity, 11.1 years simple payback time and a cost of electricity (COE) of 0.184 $/kWh.
- The sensitivity analyses revealed that the key factors that significantly affect the economic viability of the PV system are the total initial costs, electricity export rate and energy produced by the systems

Based on these findings, the development of a 60-kW grid-connected two-axis solar photovoltaic plant at the ESUT campus is both technically and economically feasible. The proposed plant can meet the electric load of the Mechanical and Electrical Engineering building as well as help towards the realization of some share of the country's solar energy generation targets. Furthermore, the exploitation of local solar resources for the proposed grid-connected PV system would contribute to Nigeria's energy security efforts and also lead to a reduction in the University's carbon footprint. The results obtained will offer interested investors and other stakeholder's information that could help them in making an informed decision regarding investment in solar PV power for the campus.

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