Journal of Energy Systems

2023, 7(1)

2602-2052 DOI: 10.30521/jes.988844 Research Article

A comprehensive analysis on the grid-tied solar photovoltaics for clean energy mix and supply in Nigeria's on-grid power

Chidiebere Diyoke*
Enugu State University of Science and Technology, Department of Mechanical Engineering, PMB 01660. Agbani, Enugu State, Nigeria, chidiebere.diyoke@esut.edu.ng
Ugochukwu Ngwaka
University of Birmingham, Birmingham, B15 2TT, United Kingdom, u.ngwaka@bham.ac.uk
Kenneth Ugwu
Enugu State University of Science and Technology, Department of Mechanical Engineering, PMB 01660. Agbani, Enugu State, Nigeria, kenneth.ugwu@esut.edu.ng

Submitted: *31.08.2021*
Accepted: *27.01.2023*
Published: *31.03.2023*

* *Corresponding Author*

Abstract: Nigeria's power infrastructure is dominated by polluting grid-connected fossil-based power systems. The Nation currently suffers from an acute electricity shortage, making nearly 40% of on-grid customers receive unreliable and inconsistent power below their demand. Solar resources are widespread in the country at considerably good potential than in many European nations. Nevertheless, Nigeria's solar photovoltaic (PV) installation capacity could be better. This paper presents the techno-economic, environmental and risk analysis of a grid-connected 10 kW, 100 kW, and 1 MW PV system for three customer segments in Abuja, Nigeria. It is found that a 1 MW grid-tied PV system is very viable at an electricity export rate not below 0.01 $/kWh and a total initial cost (TIC) of not more than 2000 $/kW for fixed axis system and 2600 $/kWh or lower for the two-axis system. The 10 kW and 100 kW PV systems are only financially viable with fiscal incentives. However, they become profitable with a minimum feed-in tariff of about 0.294, 0.297, 0.223 and 0.214 $/kWh for the fixed 10 kW, 2-axis 10 kW, fixed 100 kW and two-axis 100 kW systems, respectively.

Keywords: *Financial Analysis, Mini-grid, Nigeria Energy Resources, Renewable Energy, Solar*

Cite this paper as: Diyoke, C., Ngwaka, U., & Ugwu, K., A comprehensive analysis on the grid-tied solar photovoltaics for clean energy mix and supply in Nigeria's on-grid power. *Journal of Energy Systems 2023; 7*(1): 1-17, DOI: 10.30521/jes.988844

1. INTRODUCTION

Nigeria's populace is the seventh-largest globally, with over 211 million people [1]. There are about 42 million dwellings in the country, having a mean family size of 5.06 persons per dwelling [2]. It is projected that Nigeria's population will reach approximately 411 million in 2050 [3]. The residential and industrial sectors of the economy are projected to grow by 1 and 2%, respectively, in 2023. Electric demand will rise substantially based on the rapid development in the housing, commercial and industrial sectors. The World Bank estimated that total electricity demand would rise dramatically by fivefold in 2035 to nearly 530 TWh [4]. Nigeria's on-grid electricity demand is about four to twelvefold the electricity distributed on the grid, which is currently about 3.2 GW [5]. The country is projected to require more than 65 GW of new power-generating capacity to meet unsatisfied demand [4]. Although Nigeria has enough renewable energy (RE) sources, the country currently relies mostly on using conventional and pollution-prone fossil-based power systems to meet the Nation's energy needs [6].

The environmental effect of fossil fuel, depleting nature of fossil fuel reserves, and a forecasted future increase in national energy demand put Nigeria's energy supply security at risk. Using existing RE resource potentials will positively influence the Nation's energy demands and allow it to be less dependent on conventional, polluting, and globally traded fossil-based energy resources. Thus, it is in recognition of the necessity to match growing electricity demand sustainably that the Nigerian government has set an ambitious target to grow grid-supplied electricity from all energy mix by a minimum of 70% (30 GW) by 2030, with on-grid RE supplying 9,000 MW or 30% of the energy mix [7]. Solar PV is expected to make up 19% of this RE share [7]. The drive to increase on-grid RE proportion will not only ensure the security of energy supplies in Nigeria but also present opportunities for investment in a grid-tied RE power system. Developing grid-tied renewable power capacity in Nigeria is key to sustaining economic growth and promptly meeting the energy demand of over 40 million under-served on-grid market demand. By using locally available resources, such grid-tied RE power systems can offer a wide variety of electrical services for residential, industrial and commercial users [8].

Among the renewable energy (RE) sources, solar power is expected to play a noteworthy role in solving the twin problems of electricity supply and climate change mitigation in the country. This is because of Nigeria's advantageous geographic location that makes it possible to receive a vast quantity of distributed solar energy, ranging from 1534 to 2264 $\frac{\text{kWh}}{m^2}/year$, averaging 19.8MJ $per\ m^2 per\ day$, with over 6.5 sunshine hours per day. Solar power potential in the country is best in the northern region, with the annual Global Horizontal Irradiation (GHI) in these areas varying from 2,000 to 2,200 kWh/m^2 (see Fig. 1), which is considerably higher than in many European nations like Germany, with an average solar irradiation level of about 1150 $\frac{\text{kWh}}{m^2}/year$, where over 40 GW of solar PV is currently installed [9]. Based on estimates, if solar thermal is deployed on merely 5% of appropriate land in central and northern Nigeria, a hypothetical generation capacity of 42.7 GW could be attained. Yet, the number of solar-based power plant installations in Nigeria, particularly those tied to the grid, is insignificant.

Judging from Nigeria's solar potential and the anticipated future stricter environmental requirements for power generation, it is apparent that solar energy will become one of the main future sources of generating electricity in Nigeria. Solar PV, in particular, is anticipated to play a key part in the future energy mix in Nigeria, other developing countries and the globe due to dramatic reduction in PV cost, improved solar technology [9,10] and complementary Nigeria RE policy and diversified financing.

According to a German Energy Association [4] study, the Nigerian household sector accounts for about 58% of electricity consumption in Nigeria and the residential sector will share the highest percentage of increase in energy consumption in the next twenty-year period [4]. Also, the study projected that the demand for on-grid electricity would be more than that for off-grid electricity [4]. Thus, the housing sector possesses the vast unexploited potential for on-grid solar photovoltaic plant installations that can increase Nigeria's on-grid PV size. This will help meet Nigeria's effort to increase its solar energy percentage contribution to the total energy mix. Also, a grid-tied PV plant will help improve the current acute and consistent unreliable on-grid electricity, making nearly 40% of on-grid customers receive unreliable, inconsistent or low-quality power below their demand, often receiving less than 12 hours of electricity per day from the grid [11,12]. Among the diverse power generation sources, electric power generation by solar photovoltaic (PV) has received a huge adoption recently due to their declining cost and renewable nature [13,14]. An opportunity thus exists to supplement the electricity gap in the Nigerian grid and better serve the underserved on-grid customers through a grid-tied PV plant.

Research in solar PV is limited in Nigeria. However, many studies can be found in the literature, traversing policies and regulations, solar resource assessment and techno-economic analysis. Okoye et al. [15] carried out a solar resource potential for energy supply in Onitsha, Kano and Lagos, Nigeria. Adaramola [16] reported on the viability of on-grid solar PV in Jos, Nigeria, using HOMER. It was established that a grid-tied solar PV system could be feasible in the region. In another study by [17], the solar energy policy of Nigeria is presented, including the policy gaps and directions for the uptake and development of solar PV in Nigeria. Babajide and Brito [18] proposed domestic solar PV systems for metropolitan populations that can reduce the use of diesel generators with a potential cost saving of over 60%. The viability of meeting the off-grid electricity demand of residential buildings in Jos was presented in [19]. The cost of electricity (COE) of 0.18 $/kWh was reported for the location. Enongene et al. [20] evaluated the prospect of using solar PV systems for the power supply of domestic buildings in Lagos using the HOMER software. It was reported that the COE of the systems ranges from 0.398 - 0.743 $/kWh. Olarewaju et al. [21] used fourteen selected solar PV module types from diverse manufacturers to appraise thirteen different sites in Nigeria marked out for solar farm investment. It was reported that the COE and repayment duration lies in the range of 0.0524 -0.0607 $/kWh and 10.2–10.4 years, respectively. In a related study, Hamisu et al. [22] evaluated the impact of climatic conditions on PV systems' technical and economic performance in 31 of Nigeria's localities using RETScreen. An average COE of 0.21 $/kWh was reported across the climatic zones and lower than the grid tariff of 0.25 $/kWh. Elinwa et al. [23] used the System Advisor Model (SAM) software to evaluate the techno-economic viability of supplying three building types in Nigeria with clean energy through photovoltaic rooftop panels. The COE for each building type was reported to average 0.37 $/kWh. Owolabi et al. [24] conducted a technical, economic and environmental sustainability comparison of grid-tied solar PV systems in Northeastern Nigeria using RETScreen software. Yobe state was reported as the best site for solar PV due to its highest capacity factor (CF) of 21.7%.

1.1 Contribution to Knowledge

The literature review shows that several studies on solar PV systems for electrification in Nigeria have been done. Most of these studies [15–24] are limited to the techno-economic feasibility of a fixed-capacity solar PV system for a given location. However, this study delivers a comprehensive, multifaceted analysis combining the technical, economic, environmental, and risk analysis while considering three different sizes of grid-tied PV power systems for application in three distinct market segments in Nigeria. Comparing three different sizes of grid-tied PV power systems for different users is a promising market segment that brings increased overall system flexibility, reliability and reduced environmental pollution but remains a relatively unexplored option in Nigeria. In addition, since cost and fiscal incentives remain the two most significant hindrances to the realization of solar PV's complete potential in Nigeria, their effects on a worthwhile PV project must be properly evaluated to inspire public confidence in the investment in PV power plants in Nigeria.

The main contribution of this work is as follows:

i. Comprehensive study of the technical, economic, environmental and risk (TEEAR) analysis of three different capacity grid-connected PV systems for three Nigerian market segments. A 5 kW as a candidate for residential application, a 100 kW system for commercial/institutional applications and 1MW for utility-scale grid application in Abuja, Nigeria, per Nigeria RE policy.

ii. Given that a single price does not characterise the current PV market, parameters such as total initial costs (TIC), electricity export rate, and taxes will affect a PV project's technical and economic performance. The detailed impact of these factors, including the impact of different feed-in tariff and tax waiver rates, is evaluated with RETScreen® Version 8.0 clean energy management software [25].

iii. Since solar tracking technology can increase the energy generated by a given installed PV capacity for the same site, a comparative analysis between the fixed axis tracking systems is presented to determine the most technically and economically viable system.

Overall, the results from the study will help not only solar PV project engineers and designers but also investors and policymakers in decision-making regarding the operation and profitability of the different grid-tied PV system sizes in the country.

2. BACKGROUND INFORMATION

2.1 Nigeria Solar Resource potential

Nigeria is situated in a high sunlight belt in the West African sub-region. It has an entire land area of 923,768 km^2 [16] and is positioned at latitude 9.08º N and longitude 8.68º E. The solar radiation in the country is abundant and fairly well distributed. The duration of solar radiation is high but varies from one geographical location to the other. The average daily total global horizontal solar irradiation (GHI) fluctuates from about 4.2 kWh/m^2 per day in the coastal latitudes to about 6.4 kWh/m^2per day in the far North. Fig. 1 shows the distribution of global horizontal solar irradiation across different zones in Nigeria. Notably, the solar radiation intensity is highest in the northern part of the country (**Zone A**) – varying from 5.7–6.5 kWh/m^2per day with sunlight hours of around 6 each day and lowest in the southern part (**Zone C**) - varying from 4–4.6 kWh/m^2per day with sunlight hours of roughly 5 each day. The middle belt (**Zone B**) has average solar intensity values ranging from 4.6–5.7 kWh/m^2per day, with sunlight hours of approximately 5.5 each day.

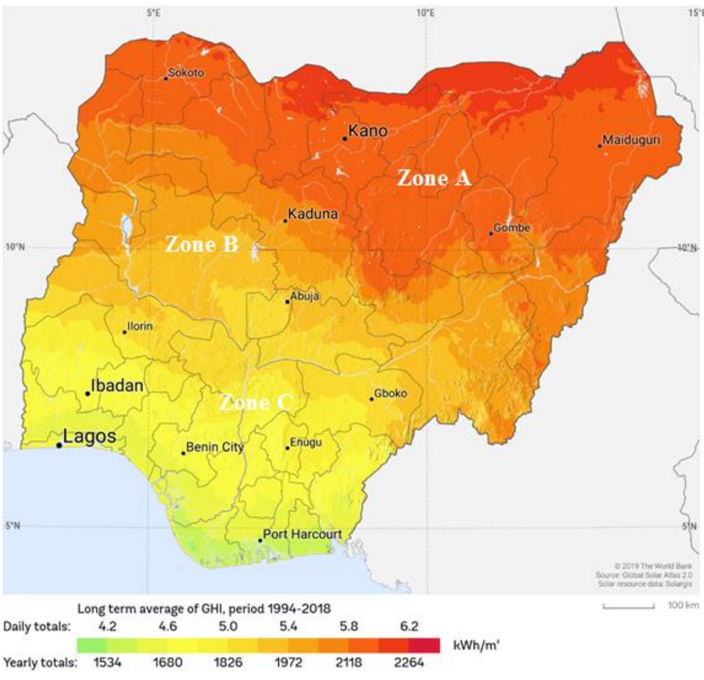


Figure 1. Global Horizontal Solar Irradiation in Nigeria. Source: Global Solar Atlas 2.0, Solar resource data: Solargis [26]

2.2 Study Location

Abuja, located in the federal capital territory of Nigeria with the geographical coordinates 9.0765º N, 7.3986º E, is chosen as the representative site of study. The average daily GHI in this location is reasonably high for solar power generation, varying from a minimum of 5.16 to a maximum of 6.7 kWh/m^2 with sunlight hours of 5.5 hours each day. This site epitomizes a place of significance regarding energy demand for the country. This is because it is the Nation's capital with moderate-high population density and economic activities but experiences an average of about 15.6 hours of electricity supply availability. This is low compared to 22.5 hours in Port-Harcourt and Kaduna Disco region and 19.4 hours in the Enugu Disco region. The variation of climate data over the year for Abuja is summarized in Table 1. The data from NASA surface meteorology in RETScreen® shows that the site experiences a mean solar irradiation of 5.9 kWh/m^2/day during the year. Table 1, shows that a substantial amount of solar radiation in Abuja can be exploited practically throughout the year.

2.3 Proposed 1 MW System

A grid-connected solar PV system consists of a PV array, energy meter, and bi-directional inverter interconnected with the local main electric grid. It is possible for energy exchange between them. In the present research, the architecture of the grid-tied PV systems is shown in Fig. 2.

Table 1. Climate data of Abuja Nigeria

Month	Air Temperature (°C)	Relative humidity (%)	Daily solar radiation horizontal (kWh/m^2/d)	Atmospheric pressure (kPa)	Wind speed at 10 m (m/s)	Cooling degree days 10 °C (°C-d)
January	20.5	26.4	5.55	95.8	3.0	326
February	23.3	20.7	6.29	95.7	3.1	372
March	27.1	19.9	6.65	95.5	3.0	530
April	30.0	31.3	6.69	95.4	2.9	600
May	30.0	48.2	6.37	95.5	2.7	620
June	28.5	59.5	5.93	95.6	2.7	555
July	26.8	68.2	5.45	95.7	2.2	521
August	25.7	75.2	5.16	95.7	1.7	487
September	26.1	72.6	5.53	95.7	1.7	483
October	26.0	56.5	5.77	95.6	1.9	496
November	23.4	35.9	5.65	95.7	2.3	402
December	20.7	31.1	5.35	95.8	2.7	332
Annual	25.7	45.6	5.86	95.6	2.5	5723

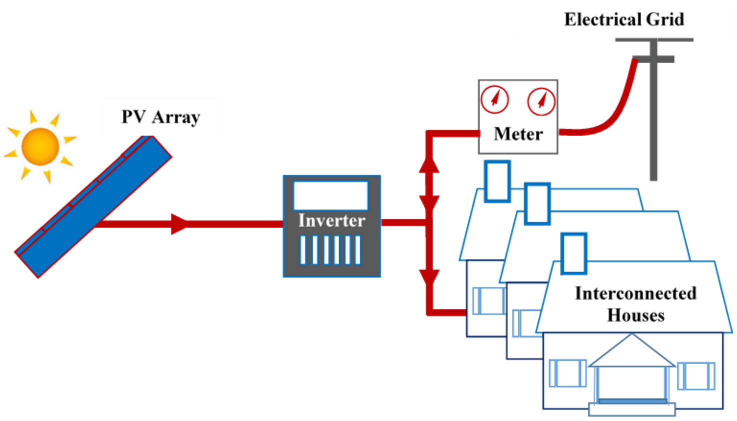


Figure 2. Typical architecture of the grid-connected PV systems

It does not involve battery equipment for backup power since the utility grid acts as the storage medium. These systems have the advantage of simplicity and, once installed, do not require extra care and service. The PV array produces a direct current (DC) output that is subsequently transformed by the inverter to alternating current (AC) electricity at the appropriate voltage and frequency for supply to the grid. The technical specifications of the three different sizes of PV systems studied are shown in Table 2.

Table 2. PV Technical specifications

	PV system sizes		
	10 kW	100 kW	1MW
PV manufacturer	China Sunergy	China Sunergy	China Sunergy
Model	Mono-Si CSUN200-72M		
Capacity per unit	0.2 kW	0.2 kW	0.2kW
No of modules	50	500	5000
Efficiency	15.67%	15.67%	15.67%
Nominal operating cell temperature	45 ºC	45 ºC	45 ºC
Inverter efficiency	97%	97%	97%

3. METHODOLOGY

The present research was performed using Version 8.0 RETScreen® software, a user-friendly clean energy management package for implementing techno-economic feasibility analysis of energy efficiency, renewable energy and cogeneration projects [25]. It also enables professionals and decision-makers to perform simulation, optimization, and sensitivity analysis to identify, assess and arrive at the optimal system configuration for potential energy projects. A key advantage of this software is that it simplifies project evaluation technique, and researchers have extensively used it with satisfactory accuracy. Some of the studies demonstrating the capability of RETScreen® in appraising the technical and economic applicability of PV systems for electricity generation in different regions of the world can be found in the works of literature [22,24,27].

The methodology adopted in carrying out the present analysis in RETScreen® consists of five key steps: *1) Sizing the PV system in an Energy model, 2) Emission analysis, 3) Financial analysis, 4) Sensitivity analysis, and 5) Risk analysis using the Monte Carlo simulation.*

3.1 Energy Model

The sizing of an on-grid PV system with no battery primarily involves selecting PV modules and an appropriate inverter. Based on the ambient temperature and solar radiation of the site of study (Table 1), the hourly energy delivered by the PV arrays to the grid can be estimated using the following equation [28]:

$$E_{grid} = \eta_{inv}\eta_{p}H_{t}A_{r} \times (1-\gamma_{r}) \times (1-\gamma_{pc}) \quad (1)$$

Where η_{inv} is the inverter efficiency, (η_p) is the average efficiency of the array, A_r is the array area, H_t is the 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 array's average efficiency (η_p) is related to the average module temperature T_c as follows:

$$\eta_p = \eta_r[1-\beta_p(T_c-T_r)] \quad (2)$$

Where η_r is the PV module efficiency at a reference temperature T_r, β_p is the temperature coefficient for module efficiency. The average module temperature T_c is related to the average monthly ambient temperature T_{amb} as follows [29]:

$$T_c = T_{amb} + (219 + 832K_t) \times \frac{(NOCT - 20)}{200} \quad (3)$$

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

Inverters are vital devices for on-grid PV systems; they change the DC power generated by the PV module into AC power. For grid-connected systems, inverters also guarantee safety by sensing instability on the grid and shutting down. Consequently, it is essential to have high inverter efficiency. For the grid-tied systems in this study, the input inverter capacity rating is set equal to the PV array rating to allow for safe and efficient operation.

3.2 Cost of Grid-tied PV Systems

The cost of grid-tied solar PV systems in Africa varies depending on the market segment and the size of the system. Based on IRENA cost data for Africa [9], the cost of commissioned and planned grid-connected utility-scale solar PV projects varied from about 1200 to 4900 $/kW in 2016, which is higher than the projected global weighted average for utility-scale projects of 1800 $/kW in 2015. For a small set of utility-scale solar PV projects, the costs vary from 1300 to 4100 $/kWh [9]. The cost of the different sizes of the PV systems used in the simulation (Table 3) was obtained from the RETScreen database [25] and is within the quoted cost range above.

3.3 Economic Analysis

The economic analysis of the hybrid power system is carried out using metrics such as net present value (NPV), cost of energy (COE), benefit-cost ratio (B-C), internal rate of return (IRR), and the payback time (PBT). The net present value (NPV) of the PV project is the value of all costs (e.g., total initial capital costs (TIC), replacement costs (RC), operating and maintenance costs (O&M) and other costs, discounted at the discount rate (r), in today's currency minus the present value of all the incomes in the project lifespan. The NPV is estimated in RET-Screen using the following formula [30]:

$$NPV = \sum_{n=0}^{N} \frac{\hat{C}_n}{(1+r)^n} \quad (4)$$

Where N is project duration, n is the analysis year, r is the discount rate, $\hat{C}$ is the after-tax cash flow which comprises capital outflow (CAPEX), operational outflow (OPEX), loan financing, incentives (if applicable) and taxes. The cost of energy (COE) is the avoided energy cost at which the net present value is zero. It is obtained by solving equation (5):

$$NPV = \sum_{n=0}^{N} \frac{\hat{C}_n}{(1+r)^n} = 0 \quad (5)$$

The internal rate of return *IRR* is the discount rate at which the NPV of the project is zero. It is estimated from the NPV in the following equation:

$$\sum_{n=0}^{N} \frac{\hat{C}_n}{(1+IRR)^n} = 0 \quad (6)$$

3.3.1 Scenario analysis

The economic analysis for this work was done by first developing a base case scenario (Scenario 1) consisting of the present PV system costs and other financial parameters, as shown in Table 3. The inverter replacement cost is assumed to be 5% of total initial costs and takes place in year 13, and the declining balance method of depreciation is used. Subsequent scenarios were then developed from this base case to help analyse the impact of incentives/grants, tax holidays and feed-in tariffs (FITs) on the profitability of the projects. In Scenario 2, the base case is assumed to benefit from a financial incentive from the federal government in year zero. This incentive is assumed to be paid for the project's initial cost; it is not refundable and is assumed as income in the construction time, year 0. The incentive is assumed to vary between 0 and 100% of the TIC. Also, in the National Renewable Energy and Energy Efficiency Policy (NREEEP) [31], power companies are usually entitled to a three-year tax holiday that may extend to five years or more; a tax holiday variation of 0-10 years is analyzed in Scenario 3. Although there are currently no feed-in tariff (FIT) rates for renewable electricity fed to the grid in Nigeria, a future FIT for RE is a certainty, as is the practice in most western and industrialized countries with safe and reliable policies and sustainable electricity. A policy on FIT is in progress and is pending approval and implementation by the electricity regulatory agencies. In Scenario 4, the base case is assumed to benefit from a future 20 year-FIT of different rates, varying from 0.15 to 0.45 $/kWh for electricity produced by the different PV systems.

Table 3. Solar PV system base case financial parameters

Cost item	*10 kW*		*100 kW*		*1 MW*	
	Fixed axis	Two-axis	Fixed axis	Two-axis	Fixed axis	Two-axis
(TIC) ($/kW)	2700	3500	2100	2600	1800	2100
O&M ($/kW-year)	33	41	25	30	22	18
Project life (years)	25	25	25	25	25	25
Inflation rate (%)	10	10	10	10	10	10
Discount rate (%)	10	10	10	10	10	10
Incentives and grants ($)	0	0	0	0	0	0
Equity/Debt ratio (%)	30/70	30/70	30/70	30/70	30/70	30/70
Debt interest rate (%)	13	13	13	13	13	13
Debt term (years)	15	15	15	15	15	15
Effective income tax rate (%)	30	30	30	30	30	30
Depreciation (%)	5	5	5	5	5	5
Tax holiday duration (years)	3	3	3	3	3	3

3.3.2 Sensitivity and risk analysis (S&A)

Costs and benefits are uncertain and may vary from the base case. Thus, to obtain dynamic results of the PV system, a sensitivity analysis of the simultaneous variation of a pair of key input parameters (O&M cost, TIC, electricity export rate and debt term) on the NPV is implemented by varying the base case values by ± 30. Additionally, under uncertain conditions, the decision maker is worried about the value of the outcome that results from the randomness of the sensitivity parameters and the degree of risk that each decision brings. Consequently, a risk analysis is carried out to quantify the probability of undesirable outcomes. Monte Carlo Simulation provided a range of likely outcomes and their corresponding frequency.

In the risk analysis, all the sensitivity parameters can vary simultaneously within a specified range. The uncertainty associated with each input parameter is specified as shown in Table 4 for the two-axis PV system, and the impact of this uncertainty on the NPV is evaluated based on a Monte Carlo (MC) simulation that includes 5,000 likely combinations of input variables resulting in 5,000 values of the financial indicator concerned.

Table 4. Variation of parameter setting for risk analysis

Perform analysis on	Net Present value (NPV)				
Number of combinations	5000				
Parameter	unit	Value	Range (+/-)	Minimum	Maximum
Initial costs	$	2,100,000	25%	1,575,000	2,625,000
O&M	$	31,500	30%	22,050	40,950
Electricity exported to grid	MWh	2,200.95	25%	1,650.71	2,751.19
Electricity export rate	$/MWh	100.00	25%	75.00	125.00
Debt ratio	%	70.00	40%	42.0	98.0
Debt interest rate	%	13.00	35%	8.45	17.55
Debt term	yr	15	25%	11	19

4. RESULTS AND DISCUSSION

4.1 Technical Performance

The technical performance of the PV system for the analyzed site was measured in terms of energy yield (EY), capacity factor (CF), emitted carbon dioxide (ECD) and carbon dioxide emission reduction (CDER). The monthly-expected output for the PV system for fixed and two-axis solar tracking systems is shown in Fig. 3 for the studied site. In January, the maximum energy yield of 1.7, 17.1 and 171.2 MWh was recorded for the fixed axis, 10 kW, 100 kW and 1 MW systems, respectively. In August, the corresponding minimum monthly energy yield was observed as 1.1, 11.0 and 109.8 MWh, respectively. For the two-axis tracking systems, the maximum energy yield of 2.3, 23.3 and 233.1 MWh was recorded in January for the 10 kW, 100 kW and 1 MW systems, respectively. The corresponding minimum monthly energy yield was observed in August as 1.3, 12.7 and 127.7 MWh, respectively.

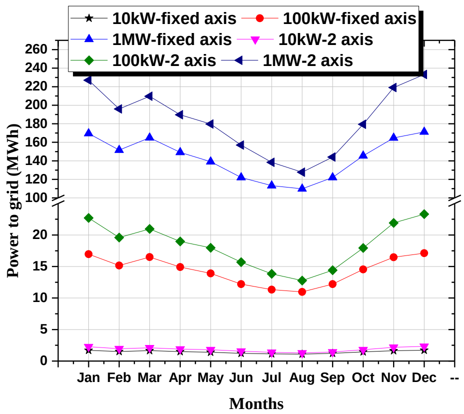


Figure 3. Energy yield of the PV systems for Abuja

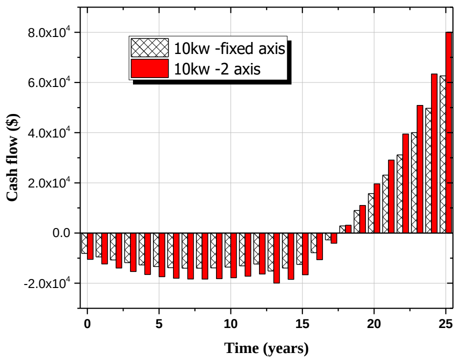
Based on the monthly values, the annual power supplied to the grid is estimated as 17.2 MWh for the fixed axis 10 kW system and 22.0 for the 2 axes tracking 10 kW system, 172.0 MWh for the 100 kW fixed axis system, and 220 MWh for the two-axis tracking 100 kW system. The energy exported to the grid by the utility-scale 1 MW system is 1723 MWh for the fixed-axis system and 2201 MWh for the two-axis tracking system. Across the three system sizes, two-axis tracking systems improved power production in the site by about 30% relative to the fixed-axis PV system. This is because the tracking system enables the PV system to follow the sun's locus over the day's progression, making the PV panels receive maximum sunshine and produce more energy. The power exported to the grid by the three different PV systems is in a linear relationship with the sizes of the PV system for both the fixed-axis and two-axis tracking systems. The capacity factor (CF), gross annual GHG emission reduction (CDER) and equivalent barrels of crude oil not consumed for using PV system instead of grid electricity from fossil fuels for the three systems are shown in Table 5. A grid-tied solar PV system can generate electricity at the site at an annual CF ranging from 19.7-25.1, depending on the type of PV system (fixed-axis or two-axis tracking system) used. This study used the potential to reduce GHG emissions from fossil-based power generation plants that make up the bulk of Nigeria's power generation infrastructure as an indicator for environmental assessment. It is found that the inclusion of a grid-tied PV system in the power generation mix in the site brings about a percentage gross annual GHG emission reduction of about 81% for each of the three PV system sizes considered, whether with a fixed or two-axis tracking system. This is equivalent to 17.3, 22.1 and 173.3 barrels of crude oil not consumed for the fixed axis 10 kW, 100 kW and 1 MW PV system sizes. The equivalent barrels of crude oil not consumed for the two-axis systems are 221.4, 733.4 and 2,214.2, respectively. Analogous to the electricity exported to the grid, the CO_2 emission also has a linear relationship with the capacity of the PV system. This means that the same impact in terms of reduction in CO_2 emission can be achieved by multiples of small or medium-scale PV system sizes or just one large-scale system to meet a given load.

Table 5. Summary of technical performance of the PV systems for three sites

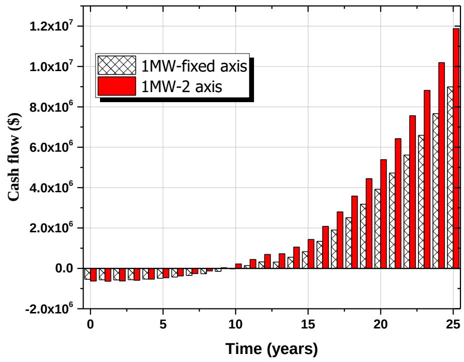
System size	PV Tracking System	Capacity factor (%)	CO_2 emission reduction (tCO_2/year)	Equivalent barrel of crude oil not consumed
10kW	Fixed axis	19.7	7.5	17.3
	2-axis	25.1	9.5	22.1
100 kW	Fixed axis	19.7	74.5	173.3
	2-axis	25.1	95.2	221.4
1000 kW	Fixed axis	19.7	745.4	1,733.4
	2-axis	25.1	952.1	2,214.2

4.2 Economic performance

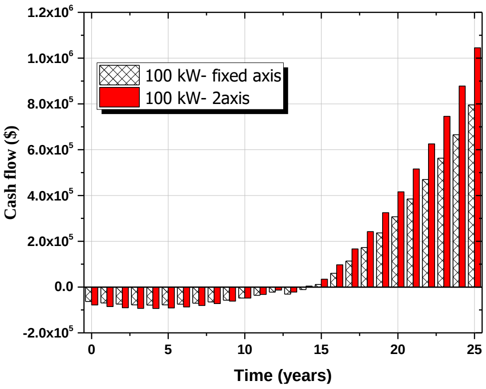
The summary of the economic performance of the three systems analyzed is highlighted in Table 6. Under the base case scenario, without financial support, a grid-connected PV system is not financially viable with both fixed and two-axis tracking PV system capacities of 10 and 100 kW in the study location because both returned a negative NPV and a benefit-cost ratio below one. However, using a utility-scale PV system of 1 MW in the study location is financially viable for both fixed and two-axis solar tracking systems. For the 1 MW system, the two-axis system has a higher financial NPV viability of $446,287 and a B-C ratio of 1.7 than the fixed axis system, with an NPV of $209,535 and a B-C ratio of 1.4. The cost of electricity of 0.176 $/kWh for the 1 MW utility system with the two-axis tracker is the lowest among the systems, followed by the COE of the 1 MW fixed axis system, which is 0.192 $/kWh. This is because of the economics of scale and low O&M cost associated with high-capacity PV systems. The COE of the 10 kW residential system with a two-axis tracking system, which is 0.298 $/kWh, is the highest because of the high O&M cost associated with residential-scale PV with a tracking system. The cumulative cash flow for the three systems against time is shown in Fig. 4 (a-c). Based on the figures, the equity payback time (PBT) for the 10kW, 100 kW and 1 MW PV systems with tracking systems for the location is about 17.6, 13.8 and 8.8 years, while for the fixed axis sizes, the equity PBT is about 17.5, 14.5 and 10.1 years respectively.



(a)10 kW



(b)100 kW



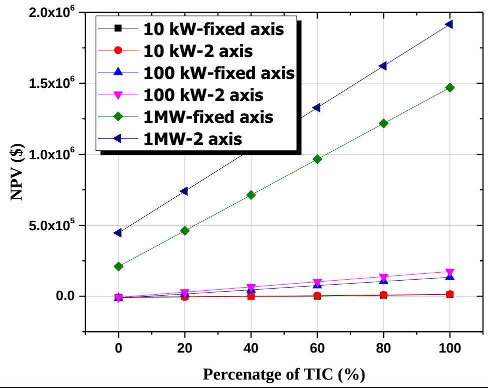
(c) 1MW

Figure 4. Equity Cash Flow

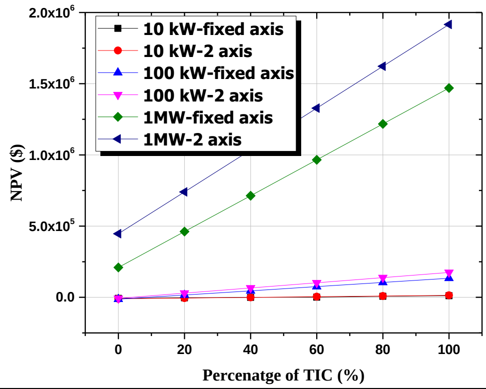
Table 6. Summary of the economic performance of the PV systems

PV size (kW)	PV tracking System	NPV ($)	COE ($/kWh)	Simple PBT (years)	Equity PBT (years)	B-C Ratio	After-tax IRR-Equity (%)
10	Fixed axis	-7,693	0.295	19.4	17.5	0.05	9
	Two axis	-10,158	0.298	19.5	17.6	0.03	8.9
100	Fixed axis	-13043	0.229	14.2	14.5	0.79	13.7
	Two axis	-7,181	0.221	13.7	13.8	0.91	14.4
1000	Fixed axis	209,535	0.192	11.7	10.1	1.4	17.4
	Two axis	446,287	0.176	10.6	8.8	1.7	19.4

As stated previously, some policies proposed to encourage the take-up and development of solar PV in Nigeria include tax waivers, favourable feed-in tariffs (FITs) and grants or incentives [31]. The impact of grants covering 0-100% of the project's TIC on the systems' NPV and COE is shown in Fig. 5.



(a) *NPV*



(b) *COE*

Figure 5. Impact on grants and incentive of the NPV and COE

As the incentive and grants increase (Fig. 5), the profitability of the systems for the site increases while the energy cost reduces. In particular, for the 10 and 100 kW fixed and two-axis tracking system sizes that are not profitable under the base case scenario. The projects will break even at a grant equivalent to 40% of TIC for a 10 kW fixed axis system; 41% for a 10 kW two-axis tracking system; 9% for a 100 kW fixed axis, and 4% of TIC for 10 kW two-axis system. The corresponding COE for the break-even points is 0.211 $/kWh for the 10 kW fixed and 2-axis system and 0.215 $/kWh for the 100 kW fixed and 2-axis system. The impact of tax holiday variation from 0 to 10 years on COE is shown in Fig. 6.

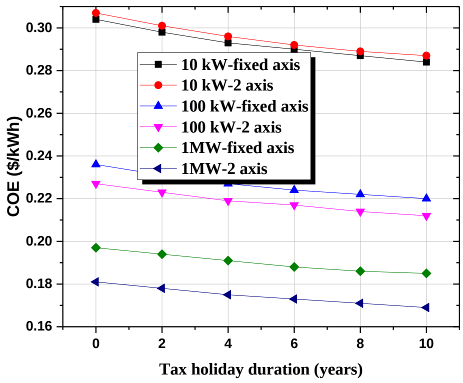


Figure 6. Tax holiday impact on COE

As can be seen, the COE declined for all the PV systems with an increase in the tax holiday. A tax holiday increase from the base case of 3 to 5 years leads to a slight reduction in COE of 1.3% for the PV systems except for the 1 MW fixed and two-axis systems, reduced by 1.6 and 1.1 %, respectively. However, if tax duration is increased to 10 years, the COE reduces by 3.73 for the fixed 10 kW system, 3.69% for the 2-axes 10 kW system, 3.93% for the fixed 100 kW system, 4.07% for the 2-axis 100 kW system; 3.64% for the fixed 1MW system and 3.98 for the 2-axis 1 MW system.

The impact of a future 20 year-feed in tariff on the internal rate of return (IRR) and the simple payback time (PBT) for the different sizes of the PV systems for the base case scenario is shown in Fig. 7. The FIT structure gives the minimum acceptable rate of return; that is, an IRR greater than the cost of capital. It can be seen that IRR varies with the different systems.

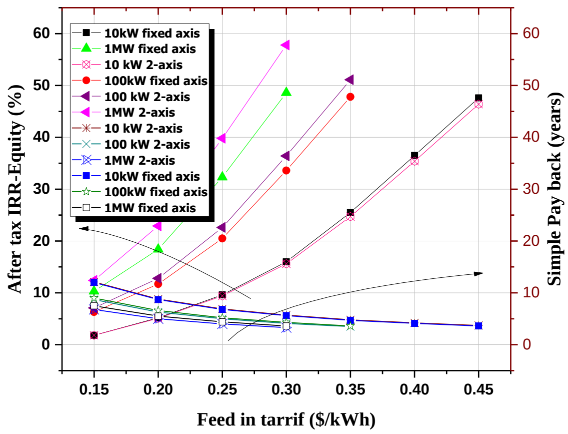


Figure 7. Impact of 20 year-FIT on performance

From Fig. 7, the simple payback time reduces as the FIT increases. Also, observe that the base case fixed and two-axis 10 kW systems can be profitable only if a minimum FIT of about 0.294 and 0.297 $/kWh is paid for generated electricity, respectively. The after-tax IRR equity corresponding to this minimum FIT is 16 and 15.6 %, respectively. For the base case fixed and two-axis 100 kW systems, a minimum FIT of about 0.223 $/kWh and 0.214 $/kWh corresponding to an IRR of 15.1 and 15% is required for the systems to be profitable. The NPV corresponding to the minimum FITs is $54.49 and $86.91 for the 10 kW fixed and two-axis systems and $574 and $186 $ for the 100 kW fixed and two-axis systems.

4.2.1 Sensitivity analysis

The following sections present the sensitivity analysis results of the 1 MW two-axis PV system as the best viable system. The sensitivity analysis considers the project parameters such as TIC, electricity export rate (EER), O&M cost, Debt rate, term and interest rate. Table 7 shows the simultaneous impact of ±30% variation in the TIC pair and EER. Both parameters influence the NPV greatly, but the NPV is more sensitive to the EER than the TIC.

Table 7. Sensitivity of a pair of initial cost and electricity export rate

		Initial costs ($)				
Electricity export rate $/MWh		1,469,930 -30.0%	1,784,915 -15.0%	2,099,900 0.0%	2,414,885 15.0%	2,729,870 30.0%
70.00	-30.0%	226,403	-38,538	-311,304	-558,434	-868,773
85.00	-15.0%	594,689	336,345	74,003	-195,017	-468,676
100.00	0.0%	962,974	704,630	446,287	185,417	-81,348
115.00	15.0%	1,331,260	1,072,916	814,572	556,228	296,832
130.00	30.0%	1,699,545	1,441,201	1,182,857	924,514	666,170

EER produces an NPV variation of about ±170% as the base value is varied by ±30%. A similar trend is observed in the TIC, where an NPV variation of ±120% is observed for ±30% change in the TIC base value. It can be seen from the figure that the implementation of the 1 MW 2-axis grid-tied PV systems is very viable at different combinations of TIC and EER. The project is highly viable at a TIC of 1500 $/kW or lower and any EER equal to or greater than 0.07 $/kWh or at a TIC of 2100 $/kW and any EER 0.085 $/kWh. In addition, the 1 MW two-axis system is viable at a TIC of 2400 or 2700 $/kWh, corresponding to EER of 0.1 and 0.115 $/kWh, respectively.

The simultaneous impact of the debt interest rate and O&M cost is depicted in Table 8. Unlike in the case of a pair of TIC and EER, the variation in the debt interest rate exerts a smaller but high impact on the NPV of the solar PV project, with variations observed not exceeding ±50% on the NPV. It can be observed that any debt interest rate below 11.05% will return a viable NPV at any TIC equal to or less than 2100 $/kWh. In addition, the project will continue to be feasible by simultaneously implementing the increase in the base case TIC and EER by up to ±15%.

Table 8. Sensitivity of a pair of debt ratio and debt interest rate

		Initial costs ($)				
Debt interest rate %		1,469,930 -30.0%	1,784,915 -15.0%	2,099,900 0.0%	2,414,885 15.0%	2,729,870 30.0%
9.10	-30.0%	1,108,279	881,072	653,865	426,658	199,451
11.05	-15.0%	1,037,153	794,704	552,256	309,808	64,321
13.00	0.0%	962,974	704,630	446,278	185,417	-81,348
14.95	15.0%	886,046	611,218	335,764	52,571	-236,125
16.90	30.0%	806,663	514,824	217,389	-88,515	-400,412

The debt ratio, Debt term and O&M costs are other parameters that affect the project outcome. It is found that they moderately affect the project outcome, resulting in variations that do not exceed ±19% over their base case NPV. Any TIC variation below 85% of TIC (1785 $/kWh) will return a possible NPV result with debt ratio, Debt term and O&M costs at ±30 variation from their base values.

4.2.2 Risk analysis

The risk analysis result showing the relative impact of uncertainty in key project parameters to the variability of NPV for solar PV projects in Abuja is shown in Fig. 8. The Figures depict how much variation in the NPV is caused by variation in electricity generated and export rate, TIC, O&M cost, debt term, ratio and interest rate.

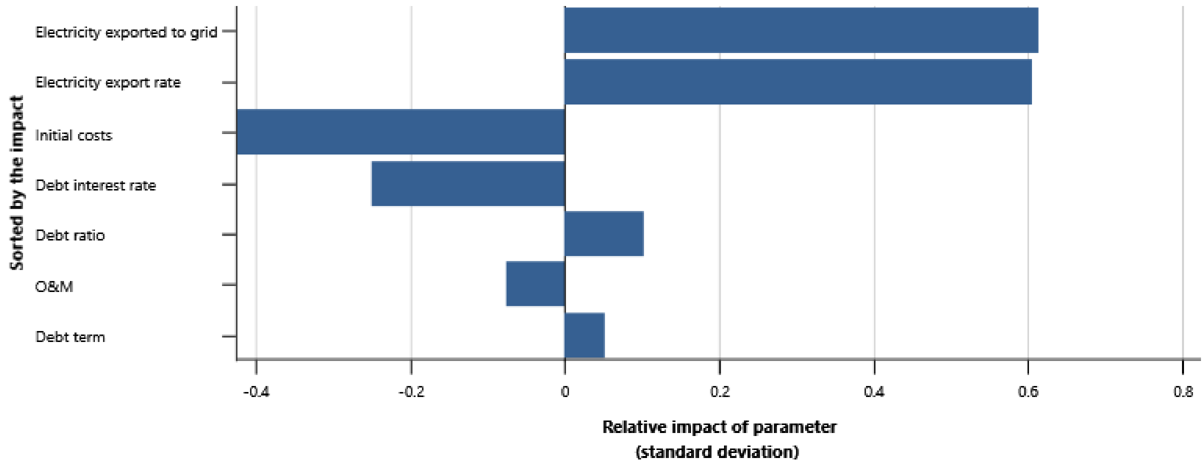


Figure 8. Relative impact of uncertainty in parameter to the variability of NPV for fixed axis solar tracker PV project in Abuja.

As already suggested by the sensitivity analysis, the electricity export rate and TIC greatly impact the project outcomes, accounting for about 60 and 45 % of its variation. They have the most significant impact on all the financial variables. Their impacts are inversely related in sign to each other. Increasing the electricity export rate increases the NPV, whereas increasing the TIC decreases the NPV. The O&M cost, debt term, interest rate and ratio also contribute apparently to the variation in the project NPV.

The histogram of the 5000 risk calculations for the NPV at a risk factor of 10% is shown in Fig. 9. This histogram shows a distribution of the possible values for the NPV that resulted from the Monte Carlo simulation. The height of each bar signifies the frequency (%) of values that lie in the NPV range defined by the width of each bar. The NPV value corresponding to the mid of each range is plotted on the X-axis. The shape of the distribution graph is relatively symmetrical, which suggests that the NPV, in this case, has a moderately low standard error. Also, the median value of $ 434,293 and expected mean of $437,077 calculated from the NPV distribution is close to the NPV value of $ 446,287 obtained in the financial analysis for the 1MW 2-axis tracking system, suggesting that the project has a low risk. Also, the confidence interval limit (min-max) is -117660 to 998527, respectively, which means that the project NPV will fall within this interval. The level of risk, which signifies the probability that the NPV will lie outside this confidence interval, is about 4%, and the probability of a positive NPV $(NPV > 0)$ is about 94.5%, which means that there is over a 94% chance and certainty that the project will be financially feasible in the studied location.

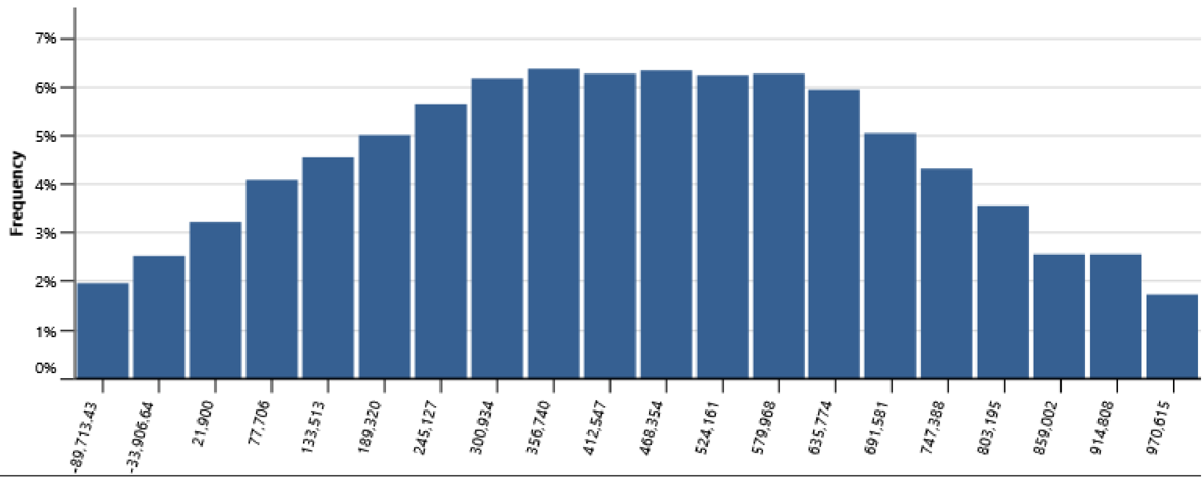


Figure 9. Distribution function of the possible NPV values for a 2-axis PV project in Abuja

5. CONCLUSSIONS AND RECOMMENDATIONS

Nigeria's power generation infrastructure comprises mostly grid-connected fossil-based power systems with total power generation capacity below National demand. Applying renewable energy (RE) based power generation systems is a favored option to improve power supply and sustainably enhance the energy mix. Solar PV is projected to be a substantial fraction of most nations' future electricity production portfolios, including Nigeria.

In this study, a comparative technical, economic, environmental and risk (TEEAR) analysis of the potential to develop three different sizes of grid-connected PV systems for three market segments: 5 kW as a candidate for residential application, 100 kW for commercial/institutional applications and 1 MW for utility-scale grid application in Abuja Nigeria was analyzed.

For each of the analyzed PV sizes, analysis was conducted for fixed and two-axis solar tracking systems. The electricity exported to the grid and capacity factor (CF) were deployed as metrics to evaluate the technical performance of the systems. For the economic performance, the net present value (NPV), cost of electricity (COE), internal rate of return (IRR) and payback time (PBT) were used as indicators from a financial standpoint. The impact of incentives such as grants, tax holidays and feed-in tariff (FIT) on the project feasibility was analyzed, including sensitivity and risk (S&R), to appraise the impact of different parameters on the performance and risk level of the project. Lastly, the project's environmental performance was assessed regarding emitted carbon dioxide (ECD) and carbon dioxide emission reduction (CDER). The following conclusion has been drawn:

In Nigeria, introducing grid-connected tracked and fixed axis 1 MW PV system size is feasible for utility-scale applications at PV array and inverter costs not above $2100/kW and $105/kW, respectively. On the other hand, 10 kW and 100 kW are only financially viable with fiscal incentives. With incentives equivalent to 40% of the total initial cost (TIC) for a 10 kW fixed axis system; 41% of TIC for a 10 kW two-axis tracking system; 9% of TIC for a 100 kW fixed axis system, and 4% of TIC for 10 kW two-axis system, the project will break even at COE corresponding to 0.211 $/kWh for the 10 kW fixed and 2-axis system; and 0.215 $/kWh for the 100 kW fixed and 2-axis system, respectively.

The utility-scale 10 kW systems will be profitable only if a minimum FIT of about 0.294 and 0.297 $/kWh is paid for generated electricity for the fixed and two-axis systems, respectively.

The utility-scale 1 MW PV system with two-axis solar tracking has a higher financial NPV viability of $446,287 and a COE of 0.176 $/kWh against an NPV of $209,535 and COE of 0.192 $/kWh for the fixed axis system.

Sensitivity analysis results indicate that the profitability of the systems is most sensitive to the electricity export rate (EER) and total initial cost (TIC) in that order. Also, it is established that implementing the 1 MW two-axis grid-tied PV systems is highly feasible with TIC of 1500 $/kW or lower and EER $\geq$ 0.07 $/kWh or at TIC of 2100 $/kW and EER $\geq$ 0.085$/kWh. Alternatively, any debt interest rate below 11.05% for the 1 MW two-axis system will return a viable NPV at any TIC variation in the range of ±30 (1500-2700 $/kWh).

Risk analysis showed that the two-axis 1 MW PV system has a low risk with a probability of a positive NPV $(NPV > 0)$ *of about 94%.*

Annual capacity factor (CF) ranging from 19.7-25.1 and a gross annual GHG emission reduction of about 81% is possible depending on the type of PV system (fixed axis or two-axis tracking system) used.

It is recommended that a way to encourage investment, particularly for the small-to-medium scale PV systems, is to apply financial incentives like tax waivers, FIT schemes, and economies of scale since higher capacity solar PV plants enjoy lower marginal investment, which makes projects offer positive returns.

The proposed plant can realize a significant share of the nation's RE generation targets and address the severe and consistent power deficiencies in Abuja, Nigeria. Moreover, utilizing the abundant solar resource of the country for power generation through grid-tied PV plants would reduce the country's carbon footprints and add to Nigeria's energy security efforts. Though the cost decline and technological growth of solar PV systems in recent years have been encouraging, the associated high cost of generated electricity compared to the existing subsidized grid tariff remain one of the factors militating against the widespread adoption of solar PV in Nigeria. For the widespread use of stand-alone and hybrid PV systems in Nigeria and globally, there is a need for further technological improvements in solar PV technologies that can reduce the cost of power generation from the system.

Conflict of interest

We declare no conflict of interest whatsoever

Data availability

The data that supports the findings of this study are available within the article

REFERENCES

[1] Word Bank. Nigeria Data 2022. https://data.worldbank.org/country/NG (accessed November 8, 2022).
[2] National Bureau of Statistics. Nigeria Living Standards Survey 2020.
[3] United Nations. World population prospects . 2017.
[4] Wedepohl D. Enabling PV Nigeria (Report No. 2517AA0484). Berlin:German Solar Association: 2018.
[5] Diyoke C, Ngwaka U, Onah TO. Comparative assessment of a hybrid of gas turbine and biomass power system for sustainable multi-generation in Nigeria. *Sci African 2021*;13:e00899. doi:10.1016/J.SCIAF.2021.E00899.
[6] Diyoke C, Ngwaka U. Thermodynamic analysis of a hybrid wind turbine and biomass gasifier for energy supply in a rural off-grid region of Nigeria. *Energy Sources, Part A Recover Util Environ Eff 2021*. DOI:10.1080/15567036.2021.1922551.
[7] Federal Government of Nigeria. Sustainable energy for all investment prospectus. Abuja, Nigeria: 2019.
[8] Diyoke C, Ngwaka U. Numerical comparison of two operating modes of thermal energy storage tank for compression heat storage in adiabatic compressed air energy storage. *J Energy Storage 2020*; 30:101558. doi:10.1016/j.est.2020.101558.
[9] IRENA. Solar PV in Africa: Costs and Markets. ISBN 978-92-95111-47-9 (Print) ISBN 978-92-95111-48-6 (PDF). 2016.
[10] Sajir H, Rahebi J, Abed A, Farzamnia A. Reduce power losses and improve voltage level by using distributed generation in radial distributed grid. *2017 IEEE 2nd Int. Conf. Autom. Control Intell. Syst., 2017*, p. 128–33. doi:10.1109/I2CACIS.2017.8239045.
[11] Blimpo MP, Cosgrove-Davies M. Electricity Access in Sub-Saharan Africa Uptake, Reliability, and Complementary Factors for Economic Impact. Africa Dev Forum Ser Washington, DC World Bank 2019. doi:10.1596/978-1-4648-1361-0 License: Creative Commons Attribution CC BY 3.0 IGO.
[12] Diyoke C, Eja LE, Ugwu KC. Hydro Backed-up Hybrid Renewable System for Off-grid Power in Nigeria. www.sciencepublishinggroup.com 2022;11:31. doi:10.11648/J.EPES.20221102.12.
[13] Ab-Belkhair A, Rahebi J, Abdulhamed Mohamed Nureddin A. A study of deep neural network controller-based power quality improvement of hybrid PV/Wind systems by using smart inverter. *Int J Photoenergy 2020*; DOI:10.1155/2020/8891469.
[14] Nureddin AAM, Rahebi J, Ab-Belkhair A. Power Management Controller for Microgrid Integration of Hybrid PV/Fuel Cell System Based on Artificial Deep Neural Network. *Int J Photoenergy 2020*; DOI: 10.1155/2020/8896412.
[15] Okoye CO, Taylan O, Baker DK. Solar energy potentials in strategically located cities in Nigeria: Review, resource assessment and PV system design. *Renew Sustain Energy Rev 2016*; 55:550–66.

DOI:10.1016/j.rser.2015.10.154.
[16]Adaramola MS. Viability of grid-connected solar PV energy system in Jos, Nigeria. *Int J Electr Power Energy Syst 2014*; 61:64–9. DOI:10.1016/j.ijepes.2014.03.015.
[17]Ozoegwu CG, Akpan PU obong. Solar energy policy directions for safer and cleaner development in Nigeria. *Energy Policy 2021*; 150:112141. DOI:10.1016/j.enpol.2021.112141.
[18]Babajide A, Brito MC. Solar PV systems to eliminate or reduce the use of diesel generators at no additional cost: A case study of Lagos, Nigeria. *Renew Energy 2021*; 172:209–18. DOI:10.1016/j.renene.2021.02.088.
[19]Akinsipe OC, Moya D, Kaparaju P. Design and economic analysis of off-grid solar PV system in Jos-Nigeria. *J Clean Prod 2021*;287:125055. DOI: 10.1016/j.jclepro.2020.125055.
[20]Enongene KE, Abanda FH, Otene IJJ, Obi SI, Okafor C. The potential of solar photovoltaic systems for residential homes in Lagos city of Nigeria. *J Environ Manage 2019*; 244:247–56. DOI:10.1016/j.jenvman.2019.04.039.
[21]Olarewaju R, Ogunjuyigbe A, Ayodele T, Yusuff A, Mosetlhe T. An assessment of proposed grid integrated solar photovoltaic in different locations of Nigeria: Technical and economic perspective. *Clean Eng Technol 2021*; 4:100149. DOI:10.1016/j.clet.2021.100149.
[22]Hamisu Umar N, Bora B, Banerjee C, Gupta P, Anjum N. Performance and economic viability of the PV system in different climatic zones of Nigeria. *Sustain Energy Technol Assessments 2021*; 43:100987. DOI: 10.1016/j.seta.2020.100987.
[23]Elinwa UK, Ogbeba JE, Agboola OP. Cleaner energy in Nigeria residential housing. *Results Eng 2021*; 9:100103. DOI:10.1016/J.RINENG.2020.100103.
[24]Owolabi AB, Nsafon BEK, Huh JS. Validating the techno-economic and environmental sustainability of solar PV technology in Nigeria using RETScreen Experts to assess its viability. *Sustain Energy Technol Assessments 2019*; 36:100542. DOI: 10.1016/j.seta.2019.100542.
[25]Leng GJ. Renewable energy technologies project assessment tool: RETScreen. Varennes, Québec: CANMET Energy Diversification Research Laboratory 1998.
[26]World Bank. Solar resource maps of Nigeria 2020. https://solargis.com/maps-and-gis-data/download/nigeria (accessed March 19, 2021).
[27]Farangi M, Asl Soleimani E, Zahedifar M, Amiri O, Poursafar J. The environmental and economic analysis of grid-connected photovoltaic power systems with silicon solar panels, in accord with the new energy policy in Iran. *Energy 2020*; 202:117771. DOI: 10.1016/j.energy.2020.117771.
[28]Diaf S, Diaf D, Belhamel M, Haddadi M, Louche A. A methodology for optimal sizing of autonomous hybrid PV/wind system. *Energy Policy 2007*; 35:5708–18. DOI: 10.1016/J.ENPOL.2007.06.020.
[29]Diyoke Chidiebere; Ugwu Kenneth C; Nnaji Anthony C. Techno economic analysis of a grid connected solar PV for a University Departmental Building in Enugu Nigeria . INT J SCI ENG RES 2021; 12:744–51.
[30]Diyoke C. Comparative Thermo-Economic and Advanced Exergy Performance Assessment of Wind Energy for Distributed Generation in Four Sites in Nigeria. *Int J Renew Energy Dev 2020*; 9:339–51. doi:10.14710/ijred.9.3.339-351.
[31]Nigeria Ministry of Power. National renewable energy and energy efficiency policy. Abuja, Nigeria: 2015.