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Potentials and financial viability of solar photovoltaic power generation in Nigeria for greenhouse gas emissions mitigation

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Abstract

Power generation processes are major contributors of greenhouse gases (GHGs), which have been linked to the global warming phenomenon, and by relying on solar photovoltaics (PV) for power generation, GHG emissions can be minimized. However, current and future power supply scenarios in Nigeria are heavily dependent on natural-gas-fired plants. Whereas the solar energy resource available in Nigeria is adequate for PV power generation, concurrent evaluations of its techno-economic feasibility and GHG mitigation effectiveness are lacking. In this study, 100-MW solar PV stations were proposed for 25 locations in Nigeria and analyzed for profitability and GHG mitigation effectiveness. Using the RETScreen software, energy and cost models were developed for each location, and GHG emissions the base (gas-fired plants) and proposed cases (solar PV plants) were analyzed. The systems proposed for high-latitude locations were found to be more profitable than those for low-latitude locations. Of the 25 locations, the proposed 100-MW PV plant in Gusau (lat. 11.88° N, lon. 6.65°) had the highest annual energy production of 167,307 MWh of electricity, a cumulative cash flow (CCF) of US$795.3 million, an energy production cost of US$66.74/MWh, a Net Present Value (NPV) of US$215 million, and a GHG reduction potential of 41,195.2 tCO_2/year. Port Harcourt (lat. 4.75° N, lon. 7.00° E) was the least favorable location with electricity production estimated at 108,309 MWh per annum, CCF at US$389.7 million, energy production cost at US$103.10/MWh, NPV at US$40 million, and GHG reduction potential estimated at 26, 668.5 tCO_2/year. The huge initial costs required for installing the systems could be recovered within 10.6 to 14 years at the locations considered, the estimated simple payback periods being between 11.6 and 18 years. An average GHG reduction payment of US$265/$tCO_2$ is recommended to improve the profitability of the solar PV plants in Nigeria.

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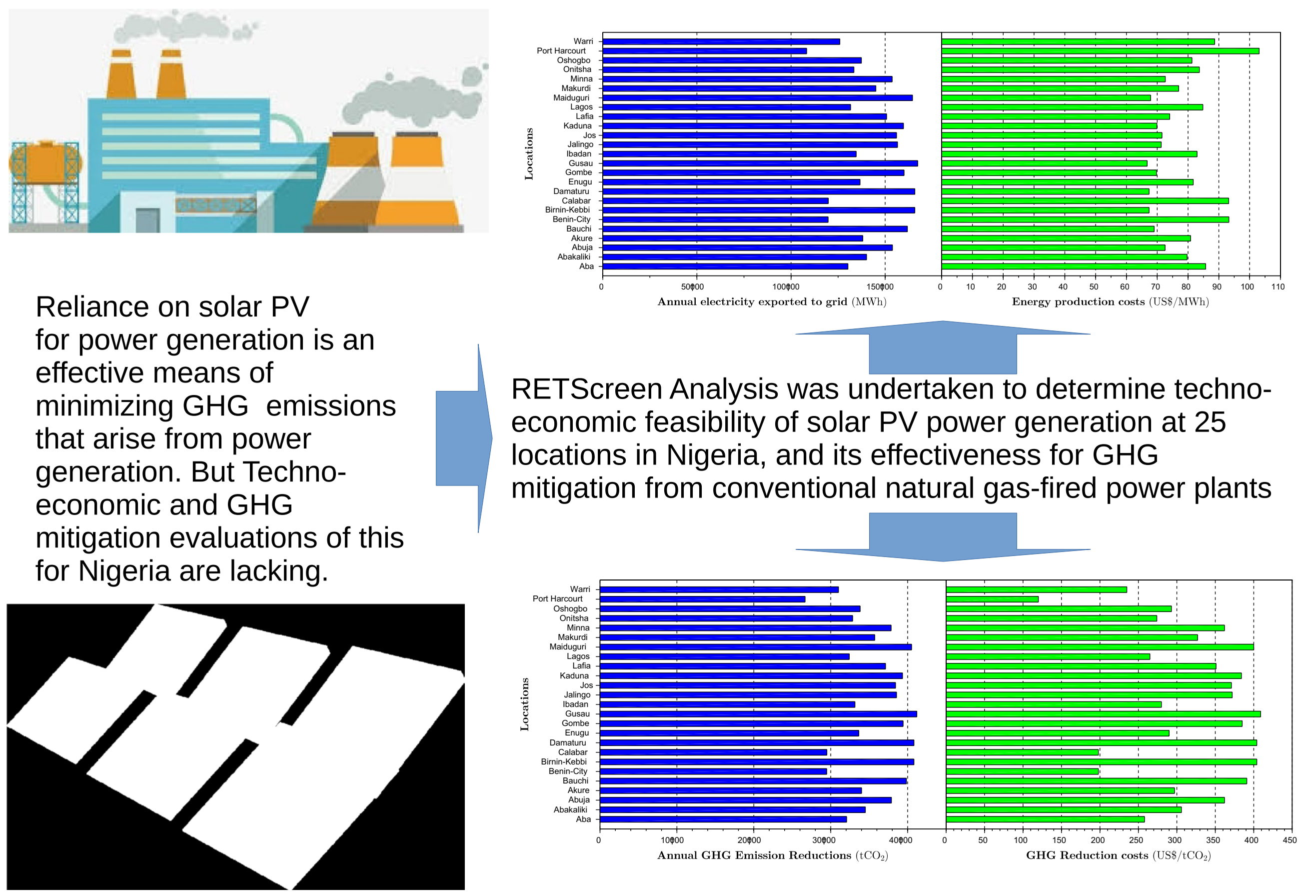
Graphic abstract



Keywords Renewable energy · PV viability · Grid-connected PV · GHG mitigation · RETScreen analysis

Introduction and study background

Energy reaches the Earth from the Sun by radiation. Some of which is absorbed by the Earth's surface, while the rest is re-radiated back into space as infrared energy. The amount of solar energy absorbed by the Earth is determined by the composition of the atmosphere because the presence of some gases prevents the escape of the re-emitted radiation, trapping and holding them in space and consequently warming the Earth. These greenhouse gases (GHGs), which include water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), etc., permit the passage of incoming solar radiation to the Earth, but restrict the flow of outgoing infrared radiation by absorbing them. These GHGs act like a blanket shrouding the Earth, by absorbing and re-radiating the Earth's thermal energy back to it. This process is natural and is counterbalanced by natural means. Energy transformation activities account for the bulk of GHG emissions, and rapid population expansions, coupled with advancements in technology and greater demands for power, will result in increased combustion of fossil fuels in engines and process plants, greatly increasing the concentration of GHGs in the atmosphere. Natural cycle processes have thus become insufficient to eliminate atmospheric GHGs, and the ensuing global warming has resulted in current efforts aimed at reducing the amount of GHGs being emitted into the atmosphere by power generation processes.

Nigeria is presently gripped by an excruciating power problem which has impacted negatively on socioeconomic progress. Official projection of demand for electric power by 2015 was ~ 14,000 MW (Energy Commission of Nigeria 2012), whereas the existing total grid-tied power generation capacity was ~ 7200 MW, resulting in a shortfall of ~ 6800 MW. This notwithstanding, due to fuel (natural gas) unavailabilities, water shortages (in hydropower plants) and sundry technical faults, power plant electricity output to the grid rarely exceeds 4000 MW and of this, the power finally delivered to consumers is in the neighborhood of 3150 MW (Advisory Power Team 2015).

Nigeria currently depends entirely on gas-fired and hydroelectric power plants for electricity generation—the gas-fired plants account for 85% of installed capacity, while hydroplants make up the rest. According to Nigeria's First Biennial Update Report to the United Nations Framework Convention on Climate Change (UNFCCC) for the period 2000 to 2015 (Federal Republic of Nigeria 2018), GHG emissions from energy transformation processes accounted for 28.2% of total emissions from the country. Within this period, GHG emissions increased from 84,815 Gg CO_2-eq in 2000 to 201320 Gg CO_2-eq in 2015, representing a mean annual increment of 6%.

The country, however, lies wholly within the sub-equatorial climate belt (within latitudes $4-14°$ N and longitudes $2-15°$ E) and experiences sunny days all year round. The total annual solar irradiation ranges from ~ 1.44 MWh/m^2 on the coasts of the Atlantic in the south to ~ 2.19 MWh/m^2 in the north, on the fringes of the Sahara (NASA 2016). The potentials for generating electricity from solar energy in Nigeria with PV technology have been estimated to be in the range of 1150–1750 kWh/kWp for fixed horizontal systems (Njoku 2014) and 1336–2487 kWh/kWp for dual-axis tracking systems (Njoku 2016). Thus, the exploitation of solar energy for electricity generation in the country seems attractive.

Besides establishing the availability and sufficiency of the solar energy resource prior to the installation of solar PV systems, there is the need to also evaluate technical and financial feasibilities and environmental impacts prior to investment decisions (Loughlin et al. 2013). Technical and financial feasibility studies on solar PV systems have been undertaken using the RETScreen Clean Energy Project Analysis software for numerous locations globally, and the environmental implications of developing such systems have also been determined. Kumi and Brew-Hammond (2013) undertook the design and analysis of a 1-MW grid-connected solar PV system to supply electricity to the Kwame Nkrumah University of Science and Technology, Ghana. The RETScreen software was used to simulate the system's performance over its guaranteed lifetime. It was found that the system had an energy yield of about 1159 MWh on an annual basis, and offered savings of about 792 tonnes of CO_2 which would have been released by a crude oil fired thermal power plant having identical energy yield. Considering the unfavorable tariff conditions in the country, a feed-in tariff scheme or other incentives such as grants and capital subsidies were recommended to make the project financially viable. A related study obtained the levelized cost of electricity from a 4.05 kWp PV system for the same location as €0.28/kWh (Quansah et al. 2017). A similar RETScreen-based study was performed by Harder and Gibson (2011) for a 10-MW photovoltaic power plant in Abu Dhabi. The energy production potential was estimated as 24 GWh at an NPV of US$44 million. The study further identified high initial costs and low expected price for generated electricity as the major hindrances to the implementation of PV systems in Abu Dhabi, and thus recommended a feed-in-tariff rate of US$0.16/kWh to make the PV system profitable.

In contrast to the studies of Kumi and Brew-Hammond (2013) and Harder and Gibson (2011) which focused on one location only, Rehman et al. (2007) carried out a detailed RETScreen analysis of electricity production potential, costs, and reductions in GHG emissions associated with installing 5-MW PV systems in 41 locations in Saudi Arabia. Of these locations, Bishah (Lat. 20.02° N, Lon. 42.60° E) was identified as the optimal location for PV plant installation based on global solar radiation and sunshine duration values. The RETScreen analysis revealed that a 5-MW PV plant in Bishah will have a NPV of ~ US$ 74 million and a simple payback period of ~ 7.6 years. Similar RETScreen studies have investigated the technical feasibility and financial performance of solar PV systems for other locations (e.g., Paudel and Sarper 2013; Sundaram and Babu 2015).

Climate change, which is linked to increasing atmospheric GHGs, is a major modern concern and the attendant global warming has opened new lines of inquiry for scientists to establish causes and effects, and proffer mitigation and adaptation strategies. As power generation processes are major contributors of GHGs, solar PV power generation has been proven to be an attractive option for GHG emission mitigation (Breyer et al. 2015). The RETScreen analysis of Rehman et al. (2007) showed that 335,455 tons/year reduction in CO_2 emissions could be achieved in Saudi Arabia if 5-MW PV power plants were installed at 41 selected locations. Performing a RETScreen analysis for 31 major sites in India, Jain et al. (2011) determined the GHG emission reduction potentials of 5-MW PV plants in India to be in the range of 1345 to 3178 tons/year. A similar study for 14 locations in Bangladesh by (Mondal and Islam 2011) found the GHG emission reduction potentials of 1-MW PV plants in Bangladesh to be in the range of 1423 to 1588 tons/year.

In other RETScreen-based studies for Quetta—Pakistan (Khalid and Junaidi 2013), Abu Dhabi—United Arab Emirates (Harder and Gibson 2011) and Safaga—Egypt (El-Shimy 2009), the potentials for mitigating GHG emissions from 10-MW fossil-fuels power plants were found to be 17,938, 10,000, and 11,930 tons/year, respectively. The sensitivity analysis performed on 22 locations in Chile by Bustos et al. (2016) demonstrated that in a GHG analysis, the GHG emission mitigation potentials depended on the base case energy source used. Thus, PV plants located in Chile's hydropower regions had less GHG emission mitigation potentials than those in regions supplied with electricity from thermal plants.

For Nigeria, the adequacy of the solar energy resource for large scale PV power generation is not in doubt, as proven by the studies of (Njoku 2014). Ohijeagbon and Ajayi (2015) assessed the possibility of supplying solar PV electricity to 40 communities hosting meteorological sites in Nigeria and found that PV systems could be profitably operated in 29 of the locations. A related study by Adaramola and Paul (2017) found that solar PV electricity feed-in tariffs of between US$0.2991 and US$0.4556/kWh were required in different parts of the country for profitable PV plants.

The choice of the locations investigated in these techno-economic analyses were arbitrary and did not generally consider access to existing grid infrastructure or proximity to population centers that would provide the demand for the generated PV power. Later, studies on solar PV systems in Nigeria evaluated conditions in just one location or region within the country, such as the study by Ajayi et al. (2016) which considered the North-East region and the study by Okoye and Oranekwu-Okoye (2018) which considered only Gusau. Most significantly, none of the foregoing studies evaluated the potentials of the PV systems to mitigate GHG emissions. The present study was undertaken to evaluate the techno-economic implications of developing solar PV power generation plants at the 25 locations in Nigeria instead of gas-fired plants. The selected locations comprise the major urban centers to which the bulk of the country's population gravitates, which are also proximate to existing grid infrastructure.

Because of the ease of deployment of gas-fired power plants, the official mid-to-long-term strategy for bridging the shortfalls in Nigeria's energy supply depends heavily on natural-gas-fired power plants, and they also contribute the bulk of current supply (Advisory Power Team 2015). Thus, 100-MW-capacity natural-gas-fired power plants were taken to be the base case in this study, while solar PV power systems of comparable peak-rated capacity were proposed as substitute cases. (In practice, the PV systems could be achieved by either constructing utility-scale installations or encouraging grid-connected rooftop-mounted distributed systems.) For each selected location, RETScreen-based financial analyses for both cases were performed, and the potentials of the solar PV systems to mitigate the GHG emissions of the conventional systems were investigated. Ultimately, the GHG mitigation costs of the proposed cases with respect to the base case were evaluated.

RETScreen analysis and methodology

The analyses embodied in this paper were carried out with the RETScreen tool. RETScreen is a decision support tool used globally to evaluate the energy production and savings, costs, emissions reduction, financial viability and risk of various types of Renewable-energy and Energy-efficient Technologies (RETs). It was jointly developed through efforts of experts from government, industry, and academia. Being a freely distributed software tool, which incorporates several equipment performance and climate databases, RETScreen greatly eases the task of comprehensively evaluating renewable energy projects (RETScreen International 2005). RETScreen analysis provides reliable results that have been established in the numerous and varied scenarios in which it has been applied (Connolly et al. 2009; Khare and Rangnekar 2014). Psomopoulos et al. (2015) compared the results of three energy prediction software (including RETScreen) and found that electricity productions predicted by RETScreen deviated from measured values by −5.8 to + 16.8% for winter periods, −20.1 to + 0.2% for summer periods, and −13.8 to −2.4% for annual outputs.

Solar energy resource and PV power generation potential

Twenty-five locations in Nigeria were selected for this study, representing the major urban centers included in RETScreen's databases. The available insolations at these locations and the populations of the enclosing states are given in Table 1. The quantity of radiation received is strongly correlated with the locations' latitudes, generally increasing with the locations' latitudes. Whereas, annually, the northernmost location, Birnin-Kebbi (Lat. 12.45° N, 4.20° E) receives 2.18 MWh/m^2 of irradiation, the next northernmost location, Gusau (Lat. 11.88° N, Lon. 6.65° E), receives the highest irradiation (2.19 MWh/m^2), while Port Harcourt (Lat. 4.75° N, Lon. 7.00° E), the southernmost location, receives the least irradiation (1.44 MWh/m^2).

Assessment of economic viability of PV systems

The economic viabilities of 100-MW solar PV plants at the selected locations were assessed on the basis of net present values (NPV), annual life-cycle savings (ALCS), cumulative cash flows, and simple payback and equity payback periods.

Net present value, NPV

The net present value, NPV, of a project is the value of all future cash flows, discounted in today's currency at current discount rate. It is given by Eq. (1):

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{\tilde{C}_n}{(1+r)^n} \tag{1}$$

where N is the project life in years and r is the discount rate. $\tilde{C}_n$ is the after-tax cash flow for year n, given by

Table 1 The solar energy resource (NASA 2016) and the populations of the states enclosing the study locations (National Bureau of Statistics 2016)

Location	Latitude (° N)	Longitude (° E)	Annual solar irradiation (MWh/m^2)	Population of location states (millions)
Aba	5.12	7.37	1.72	3.7
Abakaliki	6.33	8.10	1.84	2.9
Abuja	9.07	7.48	1.99	3.6
Akure	7.25	5.20	1.80	4.7
Bauchi	10.32	9.84	2.10	6.5
Benin-City	6.32	5.60	1.59	4.2
Birnin-Kebbi	12.45	4.20	2.18	4.4
Calabar	4.93	8.32	1.56	3.9
Damaturu	11.74	11.96	2.17	3.3
Enugu	6.47	7.51	1.80	4.4
Gombe	10.28	11.16	2.11	3.2
Gusau	11.88	6.65	2.19	4.5
Ibadan	7.40	3.92	1.79	7.8
Jalingo	8.90	11.37	2.03	3.1
Jos	9.93	8.88	1.99	4.2
Kaduna	10.52	7.44	2.06	8.2
Lafia	8.49	8.52	1.96	2.5
Lagos	6.45	3.40	1.73	12.6
Maiduguri	11.83	13.15	2.15	5.9
Makurdi	7.73	8.54	1.89	5.7
Minna	9.61	6.56	2.00	5.6
Onitsha	6.17	6.78	1.75	5.5
Oshogbo	7.77	4.57	1.78	4.7
Port Harcourt	4.75	7.00	1.44	7.3
Warri	5.52	5.75	1.65	5.7

$$\widetilde{C}_n = C_n - T_n \tag{2}$$

where C_n is the net cash flow for year n and T_n is the yearly tax value.

Annual life-cycle savings, ALCS

The annual life-cycle savings (ALCS) is the levelized nominal yearly savings which have exactly the same life and net present value as the project. It is given by Eq. (3):

$$\mathrm{ALCS} = \frac{\mathrm{NPV}}{\left(\frac{1}{r}\right)\left(1 - \frac{1}{(1+r)^N}\right)} \tag{3}$$

where the variables have all been previously defined.

Simple payback, SP

The simple payback, SP is defined as the number of years it takes for the cash flow (excluding debt payments) to equal total investment (which is a summation of debts and equity). It is given by Eq. (4):

$$\mathrm{SP} = \frac{C - \mathrm{IG}}{(C_{\mathrm{ener}} + C_{\mathrm{capa}} + C_{\mathrm{RE}} + C_{\mathrm{GHG}}) - (C_{\mathrm{O\&M}} + C_{\mathrm{fuel}})} \tag{4}$$

where IG is the value of incentives and grants, C_{ener} is the energy savings or income annually, C_{capa} is the capacity savings or income annually, C_{RE} is the annual renewable energy (RE) production credit income, C_{GHG} is the GHG reduction income, $C_{\mathrm{O\&M}}$ is the yearly operation and maintenance costs associated with the clean energy project, and C_{fuel} is the annual cost of fuel or electricity.

Year-to-positive cash flow (also called equity payback)

The year-to-positive cash flow, N_{PCF} is the first year when the cumulative cash flows for the project becomes positive. It is obtained by solving for N_{PCF} in Eq. (5).

$$0 = \sum_{n=0}^{N_{PCF}} \widetilde{C}_n \quad (5)$$

The above measures of economic viability were determined through a RETScreen analysis, using project financial parameters as inputs. These included initial project costs, annual operations and maintenance costs, periodic costs, electricity export rate, base case fuel escalation rate, inflation rate, debt interest rates, government incentives and grants, and life cycle of system components.

GHG emission reduction potential and cost

All computations related to GHG emissions were performed in the GHG Emission Reduction Analysis worksheet. The annual GHG emission reduction (Δ_{GHG}), in equivalent tonnes of CO_2 (tCO_2), was calculated based on Eq. (6)

$$\Delta_{GHG} = (e_{base} - e_{prop}) E_{prop} (1 - \lambda_{prop})(1 - e_{cr}) \quad (6)$$

where e_{base} is the base case GHG emission factor, e_{prop} is the proposed case GHG emission factor, E_{prop} is the proposed case annual electricity produced, λ_{prop} is the fraction of electricity lost in transmission and distribution for the proposed case, and e_{cr} the GHG emission reduction credit transaction fee.

For each tonne of GHG avoided, there is a levelized nominal cost to be incurred and this is referred to as the GHG Emission reduction cost GRC. It is given by:

$$\text{GRC} = -\frac{\text{ALCS}}{\Delta_{GHG}} \quad (7)$$

where ALCS is given by Eq. (3) and Δ_{GHG} by Eq. (6).

Results and discussion

Electricity exported to grid by proposed solar PV plants

The base case power sources selected for the study locations were 100-MW natural-gas-fired power plants, while the proposed cases were solar PV plants of the same capacity with fixed (non-tracking) modules. Though more power could be produced with tracking systems, fixed systems were chosen as the proposed cases to avoid the added initial, operation and maintenance costs and reduced reliabilities of tracking systems components. The technical parameters of the proposed plants are presented in Table 2.

Table 2 Technical specifications of proposed PV plant

Specification	Value
Plant capacity	100 MW
Tracking mode	Fixed
Module efficiency	12.3%
PV Module	mono-Si GE AP-120
Module temperature coefficient	0.40% (°C)
Miscellaneous PV array losses	5%
Inverter efficiency	90%
Module frame area	0.97 m^2

From the RETScreen products database, mono-crystalline silicon modules were selected for application in this study. They are based on very well-matured technologies, and have higher efficiencies and slower weather-induced aging when compared to amorphous or thin film modules (Tobías et al. 2003). The conversion efficiency of the module model chosen (mono-Si GE AP-120) is 12.3%, with a temperature coefficient of 0.40%/°C. With these solar PV plant configurations as inputs to the RETScreen analysis, the annual renewable energy produced and exported to the grid at each of the 25 sites under consideration was obtained, as shown in Fig. 1.

The quantity of electricity produced at any location depends to the largest extent on the solar irradiation on the location. Expectedly therefore, the electricity generation predicted for locations at higher latitudes such as Abuja, Bauchi, Birnin-Kebbi, Damaturu, Gombe, Jalingo, Gusau, Jos, Kaduna, Maiduguri and Minna, was higher than for the rest. Gusau, with the highest annual solar irradiation, offers the highest electricity generation (167,307 MW/year), while the least electricity generation (108,309 MW/year) was obtained for Port Harcourt, which has the least annual solar irradiation. On the average, a 100-MW PV plant located in Nigeria would generate 144,690 MWh/year.

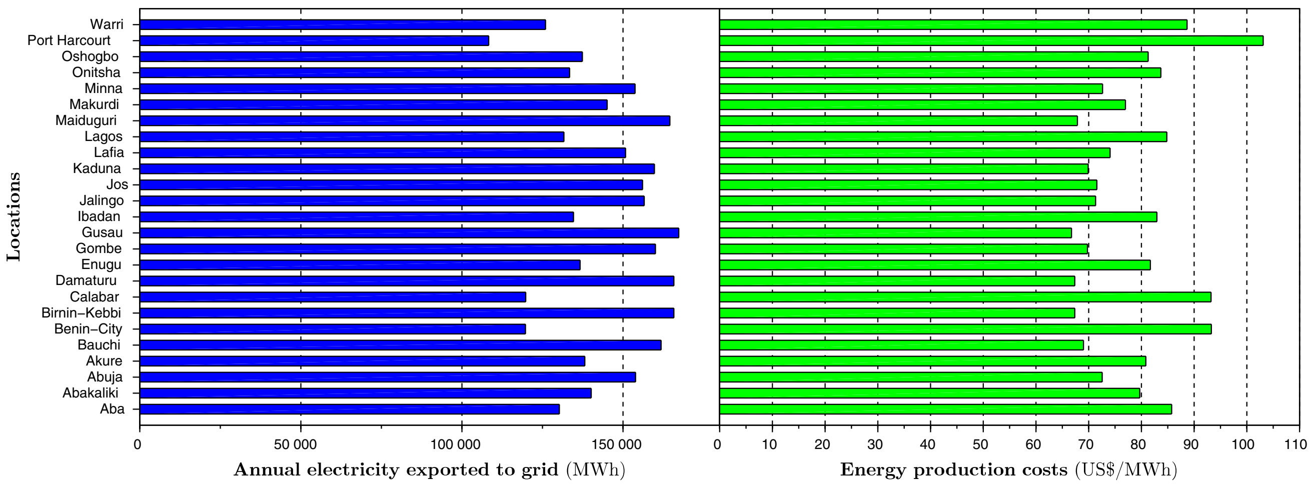


Fig. 1 Annual electricity exported to grid by proposed 100-MW PV power plants and production costs at selected locations (Table 4)

Table 3 Cost parameters for RETScreen financial analysis

Description of cost	Value (US$)	References
Feasibility study	US$ 29,200	RETScreen International (2005)
Development	US$ 63,574	Chung et al. (2015)
Engineering	US$ 94,800	RETScreen International (2005); Chung et al. (2015)
Power system	US$ 2000/kW	Goodrich et al. (2012)
Annual operation and maintenance costs	US$ 5200	RETScreen International (2005)
Transportation and accommodation	US$ 100/person	World Bank (2016)
Training and commissioning	US$ 10,000	RETScreen International (2005)

Table 4 Percentage distribution of total initial costs of proposed 100-MW PV power plants

Cost description	% Contribution to total cost
Feasibility study	0.01
Development	0.02
Engineering	0.04
PV modules	86.90
Balance of system and miscellaneous	13.03

Financial parameters are required as inputs to determine the financial feasibility and profitability of a proposed project using a RETScreen analysis. For the 100-MW solar PV plant proposed, a summary of costs used for the analysis is presented in Table 3. These costs may be classified into soft costs (costs of feasibility studies, project development, engineering, etc.) and hardware costs (PV modules, inverters and other balance-of-system components) (Chung et al. 2015). The percentage contribution of these cost components to the total initial cost of the proposed 100-MW plants is shown in Fig. 4. Due to the size of the proposed plants, the power system costs (i.e., costs of modules and balance-of-system components) account for almost the entire initial cost of the proposed PV plants.

The energy production costs for plants at each of the selected locations are also shown in Fig. 1. In contrast to the quantity of exported electricity, the average energy production costs for the proposed installations are inversely related to the solar radiation available at the locations. Hence, the higher the quantity of electricity produced, the lower its production costs. Therefore, of the 25 locations considered, the proposed plant in Gusau was estimated to produce energy at the least cost of US$66.74/MWh, while that in Port Harcourt will offer its output energy at the highest price of US$103.10/MWh. The estimates from the 25 locations show that average PV electricity production cost from a 100 MW plant is US$78.24/MWh.

Table 5 Economic variables for financial viability analysis

Description of variable	Value
Project life	25 years
Electricity export rate	US$ 118.2/MWh (Nigeria Electricity Regulatory Commission 2016)
Electricity export escalation rate	6%/year
Debt ratio	70%
Debt term	10 years
Inflation rate	8.7% (Central Bank of Nigeria 2014)
Discount rate	6%

Indicators of financial viability

The prevailing economic variables required to determine the viability of the proposed plants are presented in Table 5. Generally, the financial viability of the proposed plants greatly depended on their location. For the same plant capacity of 100 MW, the results obtained varied widely with the locations due to the differences in the intensity of solar irradiation and the corresponding disparities in the amount of electricity exported to grid and electricity production costs.

Total annual savings and income, and annual life-cycle savings

Figure 2 shows the total annual savings and incomes of the proposed plants and their ALCS. Greater annual savings and incomes will be obtained from the proposed plants in the northern locations (Abuja, Bauchi, Birnin-Kebbi, Damaturu, Gombe, Jalingo, Gusau, Jos, Kaduna, Maiduguri and Minna). For each of these locations, as shown in Fig. 2, the total annual savings and income were estimated to exceed US$ 18 million. The annual savings and income estimated for southwestern locations (Akure, Ibadan, Lagos and Oshogbo)—averaging US$ 16.01 million, were comparable to the values estimated for southeastern locations (Aba, Abakaliki, Enugu and Onitsha)—US$ 15.97 million. In the southernmost locations, the annual savings values were as low as US$ 14 million in Calabar and Benin-City and less than US$ 13 million in Port Harcourt. These were significantly less than the overall average for the 25 locations—US$ 17.10 million. It is clear, therefore, that the installation of the PV systems in the more northern locations, which receive higher solar irradiation, will result in greater savings and incomes.

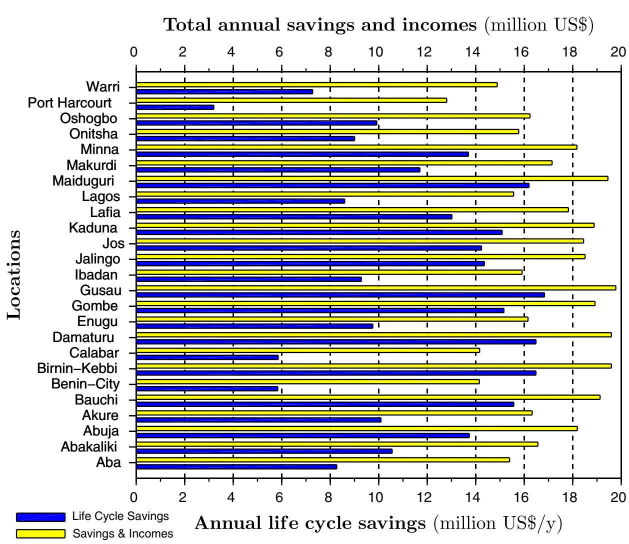


Fig. 2 Total annual savings and income and ALCS for selected locations

Figure 2 also shows that both the total annual savings and incomes and the ALCS share the same pattern of variations with respect to the studied locations. Thus, Gusau is again projected to have the highest total annual life-cycle saving of US$16,836,261/year, while Port Harcourt is projected to have the lowest value of $3,198,371/year.

Net present value

Similar to the total annual savings and income, the NPV increases with increasing power generation potential of the proposed 100-MW solar PV plant as shown in Fig. 3. Thus, the more northern the locations, the higher the NPVs that were estimated. The highest NPV of US$215,223,923 was estimated for the plant at Gusau, while the plant proposed for Port Harcourt has the lowest predicted NPV of US$40,885,915. Elsewhere, the mean NPV was US$ 120.1 million for proposed plants in the southeast and US$ 121.1 million for proposed plants in the southwest, while US$ 148.4 million was the mean NPV for the 25 locations considered.

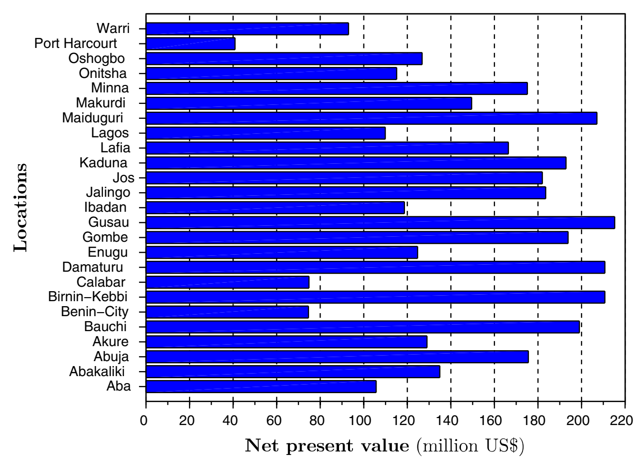


Fig. 3 NPVs for proposed PV plants for selected locations

Payback periods and cumulative cash flows for proposed plants

The payback periods (simple and equity) give general indications of how soon investments in the PV plants will start yielding profits. Hence, investments in plants with shorter payback periods will be more desirable. Figure 4 shows the simple payback periods and the equity payback periods for the locations considered. The mean values of the simple and equity payback periods were determined as 13.7 and 11.8 years, respectively. As shown in Table 6, this is well within the range of mean values obtained for other locations following similar analysis.

The project life cumulative cash flows for the different locations are shown in Fig. 4b. They vary due to the variations in the quantity of electricity that may be exported to grid from the different locations. For clearer illustration, the estimated cash flows for the proposed plant at Gusau and Port Harcourt are depicted in Fig. 5a and b, respectively. The total sum that may be realized from the proposed PV plant in Gusau at the end of its life is US$795,342,833, the project will become profitable after 10.6 years, and can fully repay its debt in 11.6 years (Fig. 4). These are the shortest simple payback and equity payback periods for the locations considered. Conversely, the proposed plant for Port Harcourt will have the longest simple and equity payback periods of 15.5 and 14.0 years, respectively. In addition to requiring the lengthiest period of time before becoming profitable, the PV

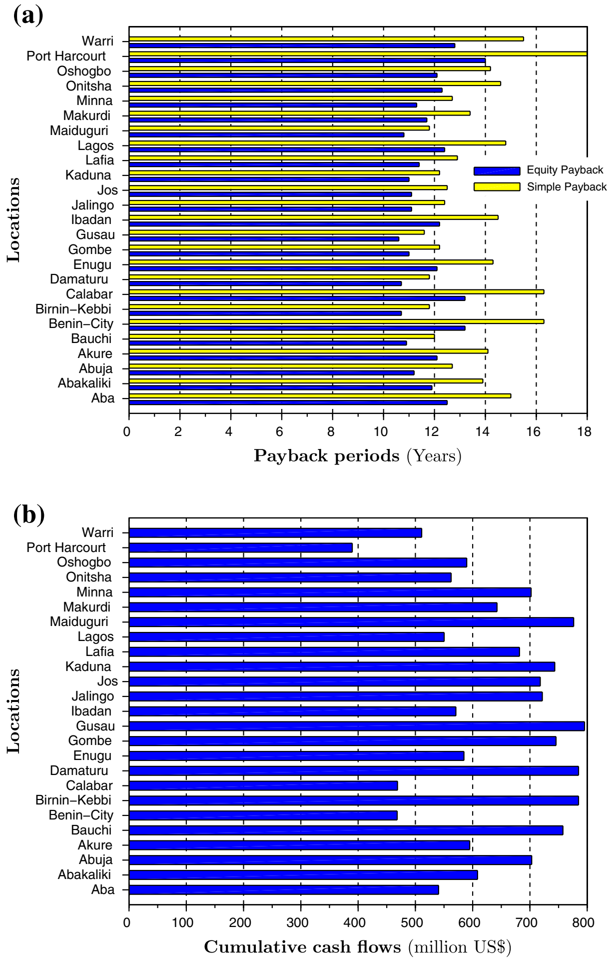


Fig. 4 **a** Simple and equity payback periods and **b** cumulative cash flows for studied locations

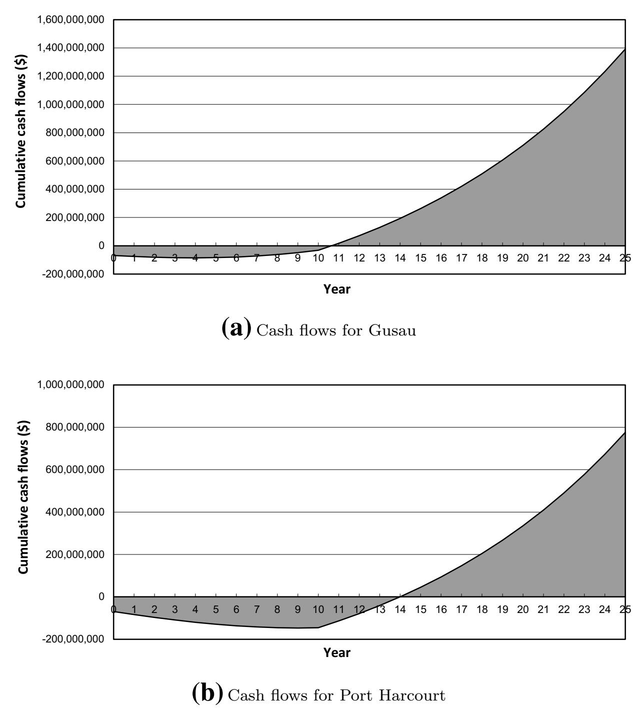


Fig. 5 Estimated cash flows from proposed 100-MWp solar PV plants at **a** Gusau and **b** Port Harcourt for 25 years project life

Table 6 Simple payback and equity payback periods previously obtained for other locations

Plant location	Plant capacity	SPP (years)	EPP (years)
Bangladesh (Mondal and Islam 2011)	1 MW	13.2	–
Egypt (El-Shimy 2009)	10 MW	–	6.08
Ethiopia (Kebede 2015)	5 MW	–	14.5
India (Jain et al. 2011)	5 MW	8.8	–
Iran (Mirzahosseini and Taheri 2012)	12 kW	40.7	12.1
Saudi Arabia (Rehman et al. 2007)	5 MW	9.6	8.2

plant proposed for Port Harcourt will also generate the least cumulative cash flow of US$389,788,116 during its lifetime.

GHG emission reduction potentials and costs

The GHG emission reductions achievable with the proposed solar PV plants, alongside emissions reduction costs, are shown in Fig. 6. Because the quantities of electricity export to grid from the different locations were not the same, even for PV plants of equal capacity (see discussion in Sect. 3.1), different GHG emission reductions were estimated for the studied locations. The net annual GHG emission reduction potentials for the studied locations was in the range of $26,668.5$ tCO_2 (for Port Harcourt) to $41,195.2$ tCO_2 (for Gusau). This translates, on a per MW basis, to $266.7 - 412.0$ tCO_2/MW, which compares well with the values obtained in other RETScreen studies for locations with climates similar to Nigeria's, e.g., $269 - 635.6$ tCO_2/MW in India (Jain et al. 2011) and $220 - 265$ tCO_2/MW in Ethiopia (Kebede 2015). In other locations that receive higher insolation and with more environmentally polluting base case power systems, much higher values have been obtained, e.g., $1327.2 - 2001.4$ tCO_2/MW in Saudi Arabia (Rehman et al. 2007) and $1193 - 1454$ tCO_2/MW in Egypt (El-Shimy 2009).

The RETScreen GHG emission analysis showed that the 25 locations possess significant potentials for avoiding the GHGs that alternative fossil-fired power plants of similar capacity would emit. This establishes clearly that reliance on solar PV plants for power generation in Nigeria will drastically minimize the emission of GHGs due to power generation activities.

Figure 6 also shows the costs of GHG reduction, which also contribute to the definition of the project's economic viability. For the proposed solar PV plants, there is a levelized nominal cost which, if adopted, will raise the financial viability of the project to optimality. These proposed GRCs vary directly with the amount of electricity produced and exported to grid. The greatest price of US$409/$tCO_2$ can be paid if the proposed plant is installed in Gusau, while the least price of US$120/$tCO_2$ can be paid for the GHG reduction by the proposed plant in Port Harcourt. The values of GRC for the other locations fall within this range, and an average GHG reduction cost of $265/$tCO_2$ was estimated to optimize the economic viability of the solar PV plants.

Conclusions

This study has simultaneously evaluated the techno-economic feasibility of solar PV power generation in Nigeria and its effectiveness in mitigating GHG emissions from conventional natural-gas-fired power plants. Solar PV power generation instead of natural-gas-fired plants at 25 locations in Nigeria was considered. It was shown that for the case of 100-MW PV plants, the quantity of electricity production, cumulative cash flows, energy production costs, project Net Present Value, and GHG reduction potentials depended the most on the insolation available at the study locations. Thus, the solar PV installations proposed for the higher latitude locations—Abuja, Bauchi, Birnin-Kebbi, Damaturu, Gombe, Jalingo, Gusau, Jos, Kaduna, Maiduguri and Minna, which receive greater insolation, were found to be more financially feasible (being more profitable and producing more electricity) than those proposed for the lower latitude locations—Akure, Ibadan, Lagos, Oshogbo, Aba, Abakaliki, Enugu, Onitsha, Calabar, Benin-City and Port Harcourt).

For the studied locations, the estimated electricity production ranged from 108, 309 to 167, 307 MW/year, at energy production costs determined to be within the range

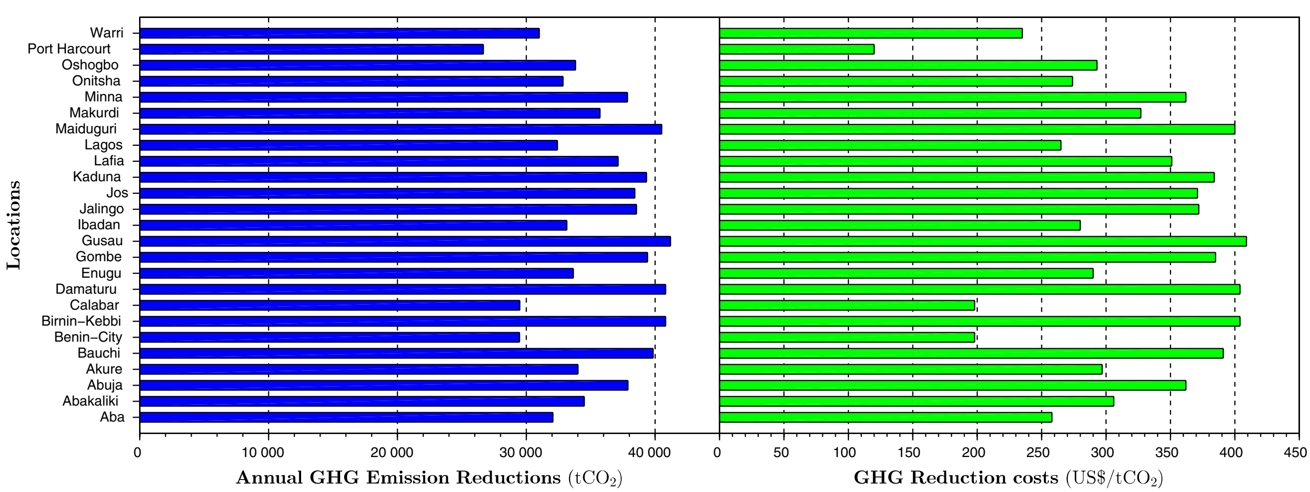


Fig. 6 Net annual GHG emission reduction potentials and costs for studied locations

of US$66.74/MWh to US$103.10/MWh. Cumulative cash flows were between US$389,788,116 to US$795,342,833, project Net Present Values were between US$40,885,915 to US$215,223,923, while GHG reduction potentials ranged from 26,668.5 to 41,195.2 tCO_2. Of all the 25 locations in Nigeria that were considered, Gusau had the best prospects for the operation of the proposed solar PV plant, while Port Harcourt was the least favorable location. Also, whereas the installation of the proposed solar PV systems will require huge capital costs, it was found that for the locations considered, these costs could be recovered within an average of 11.8 years, after which the project becomes profitable till the end of the project life.

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