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Techno-economic analysis of a utility-scale grid-tied solar photovoltaic system in Benin republic

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ABSTRACT

About 60.0% of Benin's population currently lacks access to reliable electricity to perform their daily activities. The Benin Republic has abundant solar energy resource, which could be harnessed efficiently to increase its access rate to electricity and improve living standards. This study evaluates the techno-economic viability of installing a 10.0 MW utility-scale grid-tied solar photovoltaic (PV) system in seven cities located in Benin. The RETScreen software was used to perform technical, economic, and greenhouse gas emission analyses on the proposed system. Based on the assumptions in this study, the PV system produces, on average, about 13,222 MWh/yr of electricity available for grid export. This yields a capacity factor of 15.1% and a performance ratio of approximately 67.3%. Without revenues and capital subsidies, the project generates a levelized cost of energy (LCOE) ranging from 0.110 USD/kWh to 0.125 USD/kWh. Also, the PV project is attractive for investment at a feed-in tariff of above 0.10 USD/kWh. Using the utility-scale PV plant for electricity generation at the installation sites saves about 76.0% of carbon dioxide (CO_2) emissions compared to the utility grid. The findings show that incentives and subsidies could lower the LCOE and increase solar PV investment in Benin. Investing in utility-scale PV systems could help Benin increase its electricity access rate and mitigate greenhouse gas emissions for sustainable development. The study aims to alert stakeholders, decision-makers, and investors toward developing the Benin utility-scale solar PV sector.

1. Introduction

Globally, access to energy is a key factor for socioeconomic growth (Odoi-Yorke and Woenagnon, 2021). Reliable access to electricity improves people's well-being (Altouni et al., 2022), provides quality education, and promotes good health (Odoi-Yorke et al., 2022). Africa needs to double its power generation capacity to provide universal access to affordable, reliable, and modern energy services for its population by 2030, as stated in Sustainable Development Goal 7 (SDG 7) (IEA et al., 2019). The African continent's energy sector is crucial to its economic development and provides people with the required reliable domestic energy supply (IEA, 2022).

Even though Africa currently accounts for less than 5.0% of global emissions (CDP, 2022), there is a need to transition from traditional fossil fuel usage to modern energy production practises (Sekyere et al., 2021). In view of this, programmes for energy transition have already been formed in some nations across the continent (Eshiemogie et al., 2022). For instance, in the Economic Community of West African States (ECOWAS), all fifteen (15) countries have created national renewable energy action plans with specific goals to increase renewable energy installed capacities by 2030 (IRENA, 2021).

Energy generation using solar photovoltaic (PV) technology is a central pillar of the clean energy transition (Fontaine, 2020). Solar power is one of Africa's most substantial renewable energy technologies (Maka et al., 2021), and it is now widely used in the global family of power systems (Olarewaju R. et al., 2021). Solar energy can provide rural areas with electricity without needing costly grid infrastructure (Asuamah et al., 2021). Recent studies have revealed that the average total installed cost of solar PV projects around the world that were commissioned in 2021 was 857 USD/kW, which is 6.0% less than it was in 2020 and 82.0% less than it was in 2010 (IRENA, 2022). Between 2010 and 2021, the weighted average levelized cost of energy (LCOE) of utility-scale solar PV has also decreased between 75.0% and 90.0% at individual country levels.

Benin is one of the West African countries that has set goals to deploy renewable energy systems to increase energy supply capacity. Currently, only 40.0% of Beninese have access to electricity, and access to a clean

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List of abbreviations and acronyms

ALS	Annual life cycle savings
C_f	Capacity factor
CO_2	Carbon dioxide
CO_{2e}	Carbon dioxide equivalent
C_{sav}	Yearly capacity saving
ECOWAS	Economic Community of West African States
E_d	Solar photovoltaic energy output per day (kWh/day)
$Energy_{AC}$	Alternating current electricity from inverter (kWh)
E_{sav}	Energy saving per year
F_{cost}	Annual cost of fuel
f_d	Derating factor
FiT	Feed in Tariff
GHG	Greenhouse gas
G_{STC}	Reference irradiance (kW/m^2)
HOMER	Hybrid Optimization of Multiple Energy Resources
H_{OP}	Operating hours
H_{POA}	Solar radiation on plane of PV array
InG	Subsidies
LCOE	Levelized Cost of Energy (USD/kWh)
MCA	Millennium Challenge Account
N	Project life time
NCF_t	Annual net cash flow
N_{mod}	Number of solar photovoltaic module
NPV	Net present value
O&M	Operation and maintenance
P_{ic}	Solar photovoltaic installed capacity (kW)
PR	Performance ratio
PV	Photovoltaic
r	Discount rate
SAM	System advisor model
SDG	Sustainable development goal
SDG7	Sustainable development goal 7
S_h	Peak sun hour (h/day)
SPT	Simple payback time
TC	Initial capital cost
T&D	Transmission and distribution
Xp	Annual electricity generation (kWh)

cooking system is minimal at just 6.0% in rural and urban regions (SEforALL, 2022). The government, therefore, aims to achieve an 80.0% electrification rate by 2025 with a renewable energy share of 24.6%. It plans to expand its renewable energy production capacities by 2030, eliminate the country's long-standing energy deficit, and ensure that all its citizens have access to energy by 2035 (Mensah et al., 2022).

Benin has abundant solar energy resources, with solar irradiation of approximately 5.4 kWh/m^2/day and sunshine of around 2500 h per year (Ajayi, 2013). The estimated solar PV technical potential is about 3532 MW (IRENA, 2018). Despite the country's abundant solar resources, only 8.0 MW of solar capacity had been installed by 2017 (Mensah et al., 2022). The cities in the northern parts of Benin have the highest solar energy potential. However, these cities have the lowest access rates to electricity (Odou et al., 2020). In view of this, the government is now making an effort to increase access to sustainable energy, particularly solar energy capacity, through various solar projects in the country. For example, the Millennium Challenges Account (MCA) Benin II aims to reduce the government's dependence on external importation by financing a 50.0 MW solar PV plant in Benin (MCA Benin, 2022).

Several authors have applied different numerical methods and simulation software to investigate solar PV technical, economic, and environmental performance for grid-connected applications in other countries. For example, Kebede (2015) used RETScreen software to examine the viability of deploying a 5.0 MW grid-connected solar PV system in Ethiopia. It was found that about 8674 kWh of electricity could be fed into the grid annually. However, the project is unattractive for commercial investment, though it is economically viable.

Asumadu-Sarkodie and Owusu (2016) employed RETScreen software to evaluate the economic viability of installing a 5.0 MW grid-connected solar PV system in Ghana. The authors revealed that installing a 5.0 MW PV system is economically viable in cities including Accra, Kumasi, Wenchi, and Tafo regions. Mukherjee and Razzak (2017) applied RETScreen software to analyse the financial feasibility of a 100 kW grid-tied solar PV system in different divisions of Bangladesh. The results imply that the optimised grid-connected system can reduce 166 metric tonnes of carbon dioxide (CO_2) emissions annually, equivalent to eliminating the use of approximately 30 cars and light trucks.

Other studies include Owolabi et al. (2019), who used RETScreen software to assess the feasibility of installing a 6.0 MW solar PV system in six regions in Nigeria. The authors observed that solar PV systems connected to the grid are environmentally friendly and attractive for investment. Also, Chong Li (2019) used the System Advisor Model (SAM) to evaluate the performance of grid-tied residential solar PV systems in Northwest China. The findings indicate that 5-kWp grid-connected PV systems are economically viable in the five locations. However, a grid-connected PV system with a battery is not feasible under the study conditions.

Oloya et al. (2021) assessed the techno-economic feasibility of installing a 10.0 MW grid-tied solar photovoltaic system in Uganda. The authors compared the performance of the grid-connected system over 3 years. The findings revealed that the PV system generates about 1,6702 MWh/year with an LCOE of around 0.109 USD/kWh. In Benin, FANNOU et al. (2021) simulated a 25.0 MW solar PV system, but the authors excluded economic and emissions analysis from their study. This implies that it is interesting to investigate the techno-economic viability of deploying utility-scale grid-connected solar PV systems in Benin for sustainable electricity generation.

The studies above reveal several utility-scale grid-connected solar PV systems in other countries. In view of this, none of the authors investigated the relationships between electricity generation and solar irradiation using statistical tests. Based on this gap in the literature, this study introduced a linear regression analysis to quantify the effect of solar irradiation on electricity generation and to determine the strength and direction of the relationship between the two variables. This aims to determine whether or not the relationship between the two variables is likely due to chance. The main objective of this study is to evaluate the techno-economic viability of installing a 10.0 MW utility-scale grid-tied solar PV system in seven cities, including Cotonou, Bohicon, Savè, Parakou, Djougou, Natitingou, and Kandi. The study's findings aim to inform stakeholders, decision-makers, and investors about actions that could make a utility-scale PV grid-connected project attractive for investment and deployment in Benin. This could help the government achieve its electricity generation goals by increasing energy production, building economic resilience, and reducing the country's greenhouse gas emissions.

2. Methods and materials

This section highlights the materials used, and the methodology followed to perform the techno-economic analysis of the utility-scale grid-tied solar photovoltaic system.

2.1. Site location and solar radiation

Benin is subdivided into twelve (12) regions: Atacora, Donga, Borgou, Alibori, Mono, Couffo, Zou, Colline, Atlantique, Litoral, Ouémé, and Plateau. Benin is located in the Gulf of Guinea in the Atlantic Ocean between latitudes of 6°20′ N and 12°30′ N and longitudes of 1°E and 4°E, as in Fig. 1 (Bignon et al., 2018). This study selected seven (7) cities, including Cotonou, Bohicon, Savè, Parakou, Djougou, Natitingou, and Kandi, as the utility-scale PV installation sites in Fig. 1. The selected locations are based on the availability of data. The geographical location of the selected cities, their elevation, and the annual average wind speed are presented in Table 2. Benin's solar energy potential and global horizontal irradiation increase from the south to the north, as presented in Fig. 1. Similarly, the cities' daily solar irradiation is shown in Table 3. In Benin, the annual daily horizontal solar radiation ranges from 4.89 to 5.68 kWh/m^2/day in the chosen seven cities.

Table 1
Selected cities' locations with elevation and annual average wind speed.

City	Latitude (°N)	Longitude (°E)	Elevation (m)	Wind speed (m/s)
Cotonou	6.3	2.4	9.0	4.1
Bohicon	7.2	2.1	167.0	1.6
Savè	8.0	2.5	200.0	1.3
Parakou	9.4	2.6	393.0	1.9
Djougou	9.7	1.7	384.0	2.8
Natitingou	10.3	1.4	461.0	1.6
Kandi	11.1	2.9	292.0	2.0

2.2. RETScreen photovoltaic project model

This study used RETScreen Expert Clean Energy Management Software version 8.1 to conduct a techno-economic and environmental analysis of the proposed utility-scale solar PV system. The software is extensively used for energy studies for benchmarking, feasibility, and performance analysis of different energy systems (Prasad and Raturi, 2022). Additionally, the software is used worldwide in more than 222 countries and 36 languages (Ganoe et al., 2014). It easily computes energy production, life cycle costs, and greenhouse gas emissions reductions for solar PV applications (Mirzahosseini and Taheri, 2012). The analysis framework of the RETScreen software is shown in Fig. 2. RETScreen has the ability to carry out a detailed cost analysis, financial risk analysis, and emission analysis with a strong database compared to the Hybrid Optimization of Multiple Energy Resources (HOMER) and PVSyst software (Tozzi and Jo, 2017). Photovoltaic systems include a small number of components, yet their interactions are complex. RETScreen's optimised algorithms limit data input and optimise computations while ensuring accuracy.

2.3. Technical performance analysis

This study considers a 10.0 MW grid-tied system in seven different regions to evaluate the feasibility of solar PV projects in Benin. Grid-connected solar PV systems have two main components: the PV array and the inverter. The connection to the national grid is done using appropriate inverters that must be carefully selected (Etier et al., 2015).

2.3.1. Sizing PV array

Electricity available for grid export depends on global solar radiation on the horizontal surface, the temperature, and the plant capacity factor (Asumadu-Sarkodie and Owusu, 2016). The solar PV energy output is calculated using Eq. (1) (Oloya et al., 2021):

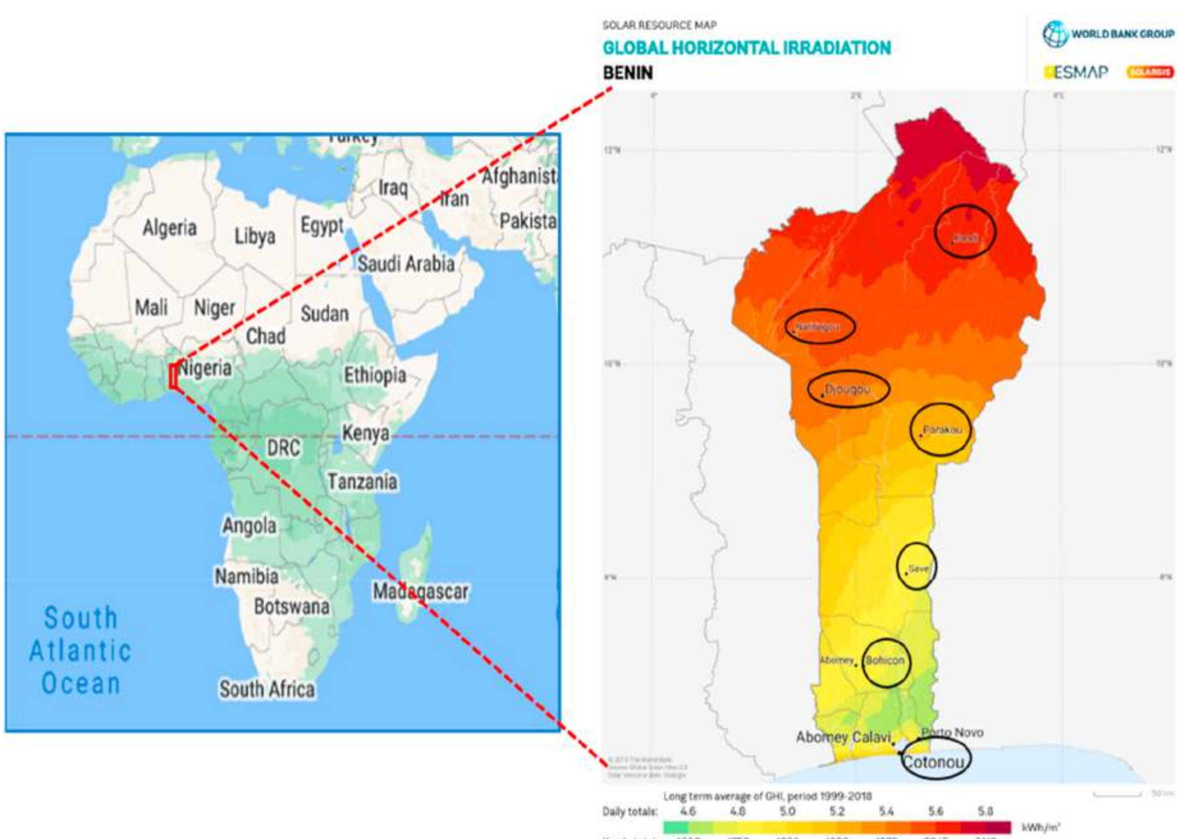

Fig. 1. Location of Benin, left: map of Africa showing the location of Benin, right: global horizontal irradiation (kWh/m^2) potential for selected cities (Global Solar Atlas, 2022).

Table 2
Daily solar radiation ($kWh/m^2/day$) for cities in Benin.

City	Cotonou	Bohicon	Savè	Parakou	Djougou	Natitingou	Kandi
January	5.33	5.48	5.58	5.58	5.55	5.46	5.41
February	5.54	5.78	5.97	6.07	6.08	6.07	6.05
March	5.49	5.73	6.02	6.17	6.09	6.15	6.25
April	5.28	5.58	5.90	6.11	5.99	6.16	6.30
May	4.94	5.30	5.56	5.77	5.65	5.85	6.14
June	4.28	4.74	4.88	5.05	5.00	5.21	5.62
July	4.31	4.28	4.29	4.53	4.56	4.74	5.11
August	4.21	4.06	4.02	4.32	4.33	4.55	4.89
September	4.37	4.37	4.39	4.67	4.75	4.94	5.35
October	4.82	4.97	5.00	5.33	5.31	5.55	5.74
November	5.01	5.24	5.50	5.73	5.70	5.71	5.77
December	5.15	5.34	5.56	5.74	5.71	5.68	5.58
Annual	4.89	5.07	5.22	5.42	5.39	5.50	5.68

Table 3
Solar PV module technical specifications (JA Solar, 2022).

Parameter	Value	Unit
Manufacturer	JA Solar	–
Module	JA P6(K)-72-320/4BB	–
Module area	1.94	m^2
Rated maximum power capacity	0.32	kW
Max voltage (V_{mp})	37.28	V
Max power current (I_{mp})	8.58	A
Open circuit voltage (V_{oc})	46.12	V
Short circuit current I_{sc}	9.09	A
Power selection	5.00	W
Temperature coefficient	0.40	%/°C
Efficiency	16.48	%

$$E_d = f_d \times S_h \times P_{ic} \tag{1}$$

Where S_h is the peak sun hours (h/day), P_{ic} is the solar PV installed capacity (kW), and f_d is the derating factor. Furthermore, the S_h is calculated as follows (Oloya et al., 2021):

$$S_h = \frac{H_{POA}(kWh/m^2/day)}{1kW/m^2} \tag{2}$$

where H_{POA} is the solar radiation on the plane of the PV array. The number of modules (N_{mod}) required for installation is computed as follows (Oloya et al., 2021):

$$N_{mod} = \frac{\text{Total watt peak rating}}{\text{PV module peak output rating}} \tag{3}$$

The solar modules would be mounted on the ground at a fixed tilt angle of 15° towards the south at an azimuth angle of 180°. Also, the derate factor (which accounts for losses due to dirt on the modules, mismatch, and wiring losses) is taken as 0.75. In Benin's market, JA

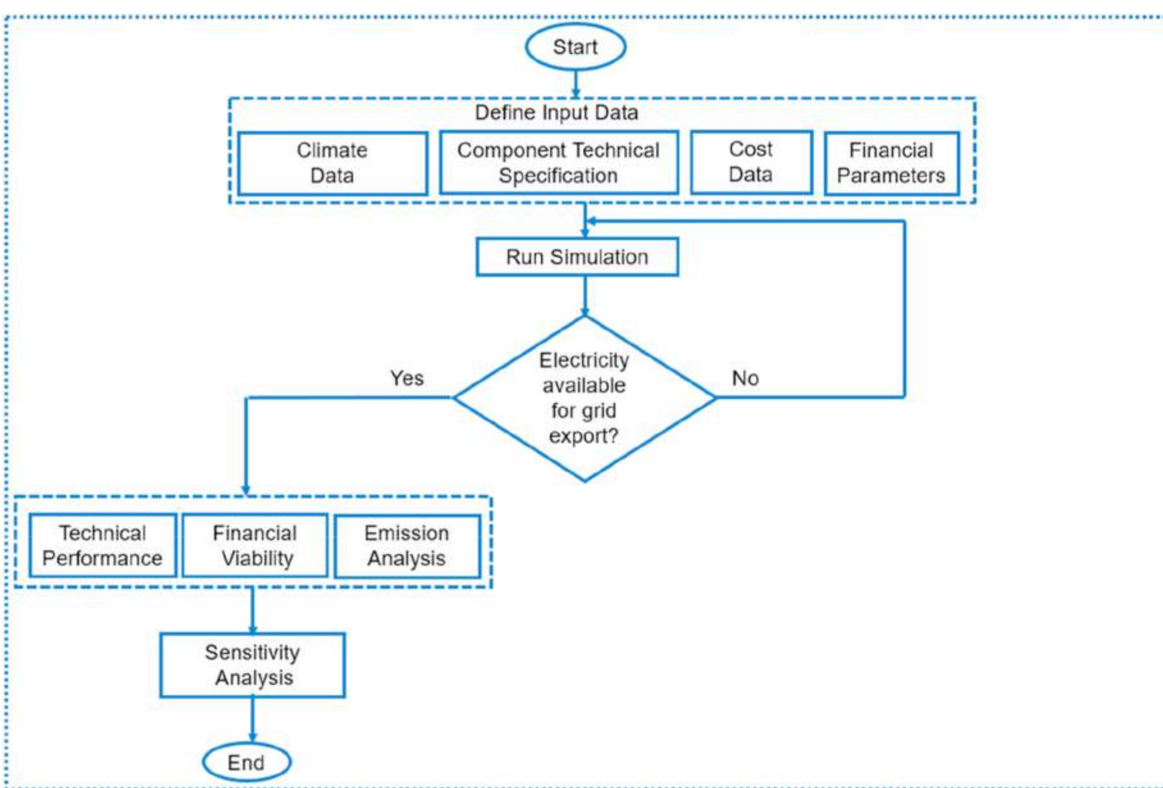

Fig. 2. Analysis framework of the RETScreen software.

multicrystalline solar modules are the most available and easy to access for power projects. The JA P6(K)-72-320/4BB module was chosen for this study since it has good efficiency at a low price in the country. Table 3 presents the selected PV module's specifications and characteristics under standard test conditions.

2.3.2. Inverter

A similar study in Egypt on a 10.0 MW grid-connected PV system recommended two inverters with a total capacity of 4750 kW and an efficiency of 95.0% (EL-Shimy, 2009). This study uses two ABB central inverters of which has capacity of 5.0 MW and 98.8% efficiency, as presented in Table 4.

2.3.3. PV system performance indicators

Typically, grid-tied PV systems' performance depends on technical indicators, including final energy output, performance ratio, and capacity factor. The performance ratio (PR) measures the percentage of losses associated with a particular PV system and can be computed using Eq. (4) (Mensah et al., 2019):

$$PR = \frac{Energy_{AC}}{PV_{rated}} \times \frac{G_{STC}}{H_{POA}} \tag{4}$$

where $Energy_{AC}$ is the alternating current electricity generated from the inverter, PV_{rated} is the rated capacity of the PV system (kW), H_{POA} is the in-plane array radiation (kWh/m^2/day) and G_{STC} is the reference irradiance (kW/m^2).

The capacity factor assesses how the 10.0 MW installed capacity is utilised for electricity generation, usually every year. The capacity factor is determined as follows (Mensah et al., 2019):

$$C_f = \frac{Energy_{AC}}{PV_{rated} \times H_{op}} \tag{5}$$

where C_f is the capacity factor of the system and H_{op} is the total operating hours during a given period (8760 h for a year).

2.3.4. PV system capital and operation and maintenance cost

Presently, Benin has no installed utility-scale PV projects. A recent study conducted in a neighbouring country like Nigeria revealed that the investment cost for a 6.0 MW grid-tied system is USD 14.4 million (Owolabi et al., 2019). Also, a 5.0 MW solar PV grid-tied project's initial capital cost was approximately USD 19.0 million in Ethiopia (Kebede, 2015) and USD 18.0 million in Ghana (Asumadu-Sarkodie and Owusu, 2016). However, a 10.0 MW centrally installed grid-tied PV system costs USD 19.0 million in Uganda (Oloya et al., 2021). In August 2022, the government of Ghana commissioned a 13.0 MW solar power project at Kaleo in the Nadowli-Kaleo District for a total cost of EUR 20.2 million. Nowadays, solar PV system prices keep decreasing (IRENA, 2022), and in the Benin market, a 320 W multicrystalline JA Solar costs around USD 200. Based on existing investment costs for similar projects in other African countries, the initial investment cost is taken as USD 18,500,000. The cost breakdown for each component is summarised in Table 5. In this study, the selected PV module and inverter have no replacement cost since the component's lifespan equals the project's lifespan. After consultation with experts, the operation and maintenance (O&M) cost is estimated to be 13.0 USD/kW-yr. This O&M cost includes cleaning modules, tightening loose cable lugs, and cable replacement.

Table 4
Inverter technical specifications (Solar inverters, 2022).

Parameter	Value
Model	PVS980-58 – 5000 kVA
Capacity	5000 kW
Grid type	On-grid string inverter
Peak efficiency	98.8%
Maximum DC power input	10000 kWp
Output (AC)	
Power at 25 °C	5000 kW
Nominal output voltage	690 V

Table 5
Breakdown of initial capital cost components.

Parameter	Value	Sources/remarks
Feasibility study, development, and Engineering	0.6% of the initial cost	(Kebede, 2015; Owolabi et al., 2019)
Photovoltaic module	70.4% of the initial cost	Asumadu-Sarkodie and Owusu (2016)
Balance of system	24.0% of the initial cost	Asumadu-Sarkodie and Owusu (2016)
Miscellaneous	5.0% of the initial cost	Asumadu-Sarkodie and Owusu (2016)

2.4. Economic metrics for decision making

Financial analysis is a crucial part of any project's development for decision-making. The critical economic metrics for decision-making comprise the net present value (NPV), LCOE, annualised cost, and simple payback time. Table 6 is a summary of essential financial input parameters that are used to estimate the output metrics.

2.4.1. Net present value (NPV)

NPV is the difference between the present value of projects' cash inflows and outflows. The NPV is computed using Eq. (6) (Prasad and Raturi, 2022). An investment is financially acceptable if the NPV is positive and is not acceptable if it is negative.

$$NPV = \sum_{i=0}^{n} \frac{NCF_t}{(1+r)^t} = -C_o + \sum_{i=1}^{n} \frac{NCF_t}{(1+r)^t} \tag{6}$$

C_o is the investment cost, r is the discount rate, n is the project's economic life, and NCF_t is the annual net cash flow for the year t (Oloya et al., 2021).

2.4.2. Levelized cost of energy (LCOE)

LCOE is the lifetime cost to construct and operate the solar PV project divided by its lifetime energy output. Also, the LCOE is the lowest cost at which electricity must be sold for a project to break even during its lifetime (Olarewaju R. et al., 2021). It is expressed by:

Table 6
Financial input parameters for decision making.

Financial parameter	Value	Comments/source
Debt ratio	70.0%	Higher debt ratios indicate greater financial leverage for a project. The model uses the debt ratio to calculate project equity investment. The most common debt ratio is 50.0–90.0%.
Debt interest rate	6.3%	The available debt interest rate at the study time (World Bank, 2022c).
Reinvestment rate	9.0%	This is the rate used to reinvest positive cash flows to calculate the modified internal rate of return.
Debt term	15.0 years	This refers to how long the debt is repaid. Debt term equals or is shorter than project life. Longer terms improve a project's financial viability. The model calculates debt payments and yearly cash flows using debt terms. Typical debt terms range from 1.0 to 25.0 years.
Energy escalation rate	5.0%	This is the annualised fuel cost increase over the project's life.
Discount rate	5.0%	The rate used to discount future cash flows to obtain their present value
Inflation rate	3.0%	Current inflation at the study time (World Bank, 2022b).
Project lifetime	25.0 years	Typical solar PV project lifetime used to assess the project's financial viability.

$$\text{LCOE} = \frac{\text{Life Cycle Cost (USD)}}{\text{Life energy production (kWh)}} \quad (7)$$

2.4.3. Annual life cycle savings

The annual life cycle savings is the levelized nominal annual savings with the same life and NPV as the project. It is calculated as follows (Kebede, 2015):

$$\text{ALS} = \frac{\text{NPV}}{\frac{1}{r}\left(1 - \frac{1}{(1+r)^N}\right)} \quad (8)$$

Where ALS is the annual life cycle savings, r is the discount rate, and N is the project lifetime.

2.4.4. Simple payback time

The simple payback time (SPT) is the years required for the cash flow to equal the initial investment. Also, it represents the time it takes an owner to recoup its initial cost through revenues or benefits. Eq. (9) is applied to compute the simple payback time (Aboagye et al., 2020):

$$\text{SPT} = \frac{\text{TC} - \text{InG}}{(E_{sav} + C_{sav}) - (OM_{cost} + F_{cost})} \quad (9)$$

Where TC represents the project's initial capital cost, InG represents subsidies such as incentives and grants, E_{sav} represents the energy savings per year, C_{sav} represents the yearly capacity savings, OM_{cost} represents the annual operation and maintenance cost and F_{cost} represents the annual cost of fuel or electricity.

2.5. Greenhouse gas emissions and savings

The model estimates greenhouse gas (GHG) emissions for the solar PV system as follows (Kebede, 2015):

$$GHG_{em} = GHG_{ef} * E_{grid} * \gamma_p \quad (10)$$

Where GHG_{em} is the greenhouse gas emitted by the PV system (tCO_2), GHG_{ef} is the greenhouse gas emission factor (tCO_2/kWh), E_{grid} is the electricity available for grid export (kWh) and γ_p is PV system's electricity transmission and distribution (T&D) losses. Electricity transmission and distribution losses are taken to be 18% (Asumadu-Sarkodie and Owusu, 2016). The annual greenhouse gas emission reduction is estimated using Eq. (11) (Kebede, 2015):

$$GHG_r = (E_b - E_P)X_p(1 - \gamma_p) \quad (11)$$

where GHG_r is the annual GHG emission reduction (tCO_2) E_b is the grid GHG emission factor (tCO_2/kWh), E_P is the PV system's GHG emission factor (tCO_2/kWh), and X_p is the PV system's annual electricity generated (kWh).

3. Results and discussions

The main findings of the study are presented and discussed in this section. It provides discussions on electricity production, performance ratio, capacity factor, economic indicators, and GHG emission analysis of the proposed system.

3.1. Electricity production

Fig. 3 shows each installation site's monthly electricity generation and solar irradiation. It is seen that electricity generation follows the same trend as solar irradiation. Also, electricity generation varies among the sites. The sites in the northern region, such as Kandi and Natitingou, have the highest electricity generation. This is due to the fact that Benin's solar energy potential and global horizontal irradiation increase from the south to the north. However, the annual electricity generation

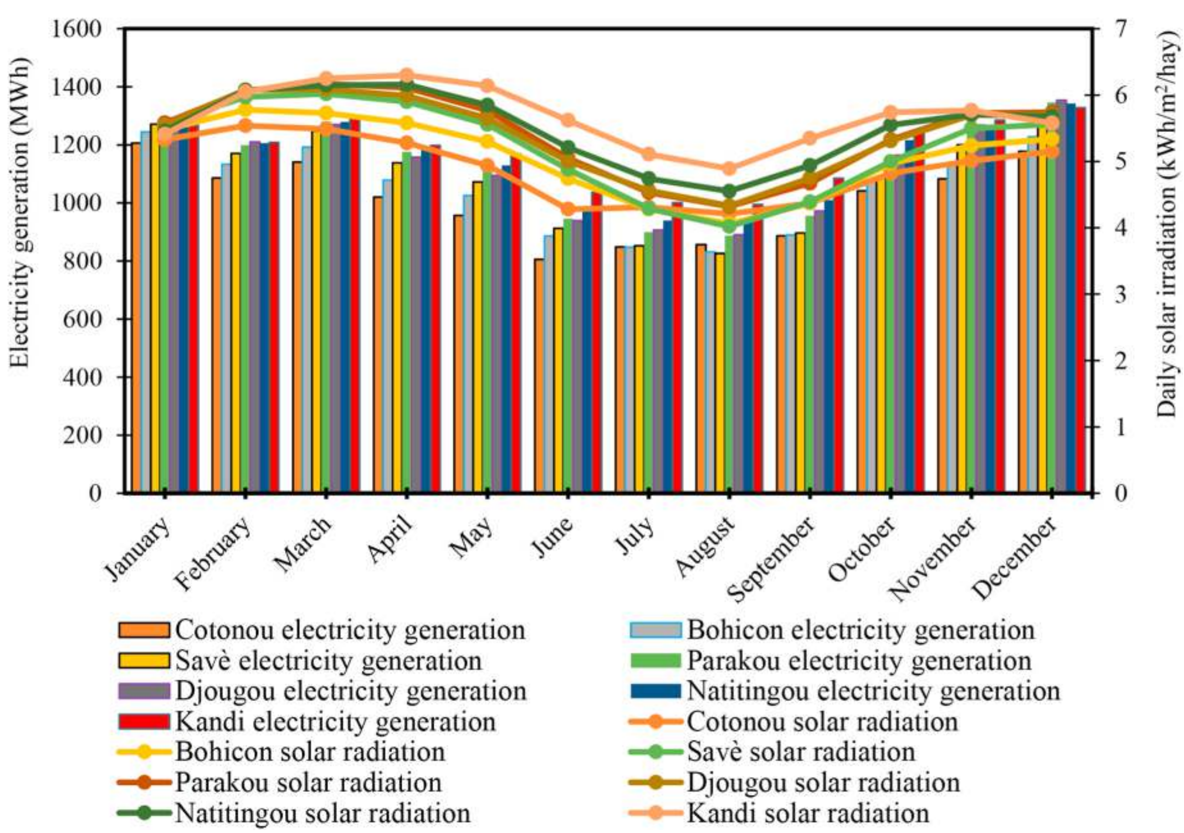

Fig. 3. Installation sites' monthly average electricity generation and solar irradiation.

differences among the sites are very close. For instance, the difference between the highest and lowest generations is about 15.3%. This implies that each site has a significant potential for solar PV deployment. Generally, electricity generation is dependent on solar irradiation. Therefore, the correlation coefficient (r), which examines the strength and direction of the linear relationship between electricity generation and solar irradiation for each site, is presented in Fig. 1A–7A. It can be deduced from the results that there is a positive linear correlation between electricity generation and solar irradiation for the seven sites. However, the r values vary among various installation sites. It is also observed that some sites exhibit high r values while others exhibit moderate r values. For example, cities with r = 0.7–0.8 include Parakou, Natitingou, Bohicon, Djougou, Cotonou, and Savè (Figs. 1A–6A). The implication is that there is a high correlation between electricity generation and solar irradiation. On the other hand, there is a moderate correlation (r = 0.589) between electricity generation and solar irradiation for Kandi (Fig. 7A). Based on the r values, the ranking of the sites in terms of highest correlation is as follows: Savè > Bohicon > Cotonou > Parakou > Djougou > Natitingou > Kandi.

Furthermore, it can be gleaned from Fig. 3 that electricity generation varies among the sites for each month. Also, electricity generation is lower for each installation site from June to September. This is due to lower solar irradiation caused by cloudy skies and frequent rain. The average electricity generation from the seven installation sites is about 13,221.7 MWh/yr. According to the World Bank (2022a), Benin's annual electricity consumption per capita is about 100.225 kWh. This indicates that approximately 131,920 people could be supplied with electricity from the 10.0 MW solar power plant using 13,221.7 MWh as the benchmark. In addition, this is equivalent to providing electricity to about 16,490 households using 8 people as a household size. Therefore, the electricity supplied to the grid could satisfy Benin's households' electricity needs. As of 2020, only 41.4% of Beninese had access to electricity (World Bank, 2022a) out of a population of 12.5 million. Based on this current data, it can be deduced that using the 10.0 MW solar power plant for electricity generation could increase Benin's electricity rate by about 1.8%. This means that putting in the 10.0 MW at all the suggested sites could give about 12.0% more people access to electricity.

3.2. Performance ratio and capacity factor

Fig. 5 shows various sites' annual performance ratios and capacity factors for the 10.0 MW solar PV power plant. The capacity factor increases with higher electricity generation. Generally, a power plant with a capacity factor of 100.0% produces electricity continuously. It can be seen that the annual capacity factor varies between 13.8% for Cotonou (the lowest) and 16.1% for Kandi (the highest), with an average of 15.1%. This infers that capacity factors for the installation sites are very close. Also, the estimated PV capacity factor is nearly comparable to the global average capacity factor of about 17.0% for utility-scale solar PV (Madhumitha, 2022). Besides, the performance ratio indicates the fraction of energy losses associated with the solar PV system. A key observation from Fig. 5 reveals that the annual performance ratio ranges between 66.8% in Kandi (the lowest) and 67.5% in Cotonou (the highest), with an average of 67.3%. This suggests that the sites' PV installation performance ratios are very comparable. The lower performance ratio is due to losses attributed to the PV system. This comprises losses due to inverter inefficiency, wiring systems, soiling modules, dust accumulation on modules, high ambient temperatures, and low wind speeds.

3.3. Economic indicators

Table 1 presents the economic metric output for the utility-scale grid-tied PV systems without revenues. This is based on the assumption that electricity from the solar PV system is fed into the utility grid without obtaining revenues from electricity sold or capital subsidies such as grants and incentives. It can be seen in Table 7 that the NPV for each solar PV plant is negative, making the project unattractive for investment. This suggests that a developer or an investor cannot recoup its investment, as shown in the simple payback time, since the annual costs incurred are higher than the annual savings generated. Nevertheless, the PV systems show a promising LCOE for each installation site. The results indicate that the LCOE decreases with higher electricity generation. The LCOE varies from 0.110 USD/kWh to 0.128 USD/kWh, with an average value of 0.120 USD/kWh. The average LCOE (0.12 USD/kWh) is similar to the LCOE obtained in similar studies in Uganda (Oloya et al., 2021) and Ghana (Obeng et al., 2020). However, the LCOE is about 63.0% lower than the LCOE obtained in Ghana (Asumadu-Sarkodie and Owusu, 2016). The difference in the LCOE might be due to the installed capacity used for assessment. For instance, Asumadu-Sarkodie and Owusu (2016) analysis was based on a 5.0 MW utility-scale grid-connected PV system, compared to the 10.0 MW employed for this study. Therefore, the LCOE is expected to decrease as the plant capacity increases because of economics of scale. Conversely, a recent survey by IRENA (2022) has revealed that the global weighted LCOE of new utility-scale solar PV projects is about USD 0.048/kWh, which is about 85.0% lower than the average LCOE estimated in this study.

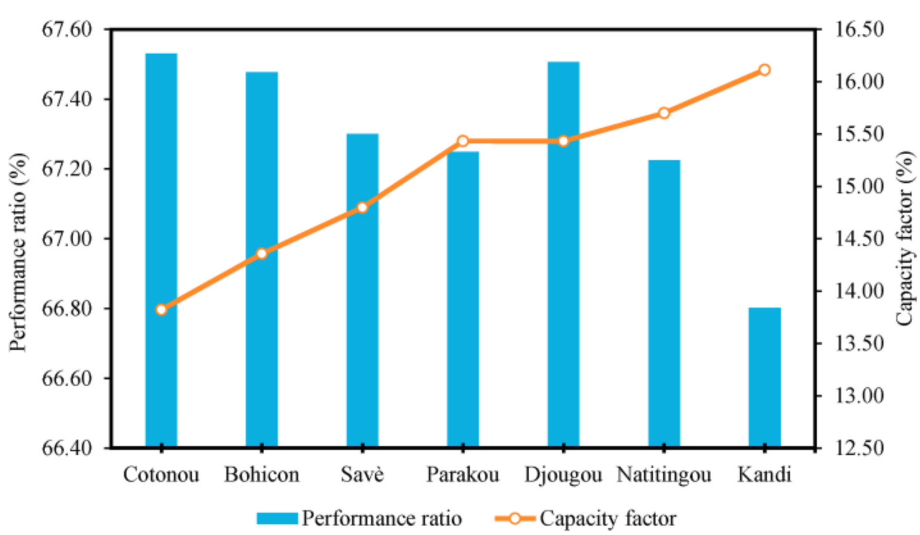

Fig. 4. Installation sites' annual performance ratio and capacity factor.

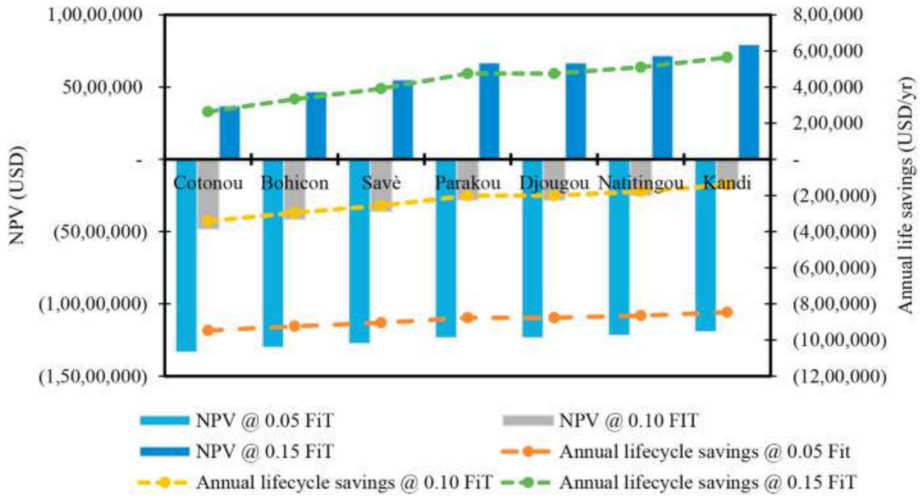

Fig. 5. Impact of feed-in-tariffs on NPV and annual lifecycle savings.

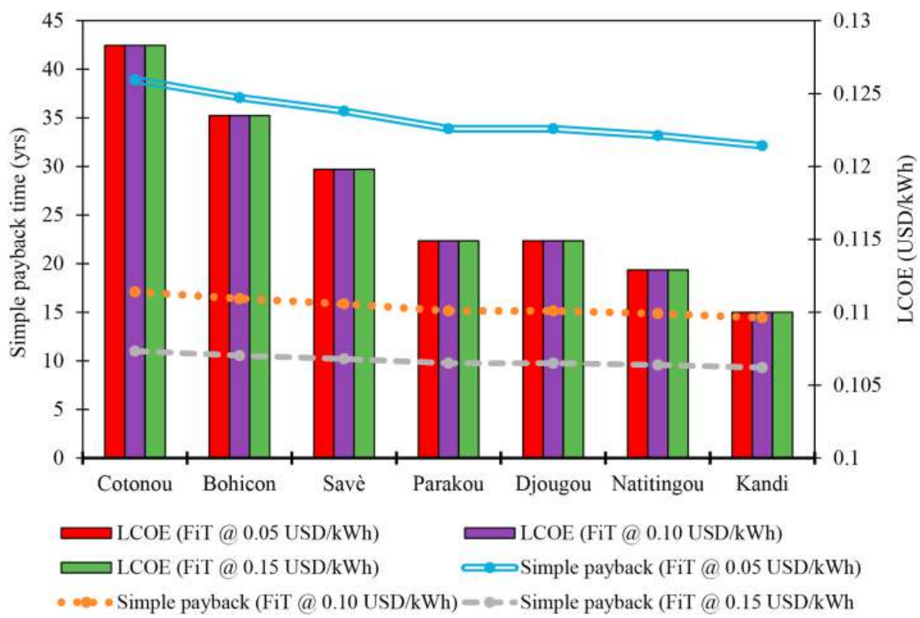

Fig. 6. Impact of feed-in-tariff on LCOE and simple payback time.

Furthermore, four different capital subsidies (25.0%, 50.0%, 75.0%, and 100.0%) were applied to the system to investigate their impact on NPV and LCOE, as shown in Table 8. It can be observed that NPV declines significantly as capital subsidies increase. Nevertheless, the projects still yield a negative NPV, even at a 100.0% capital subsidy. The implication is that the project is still unattractive for investment, despite having obtained 100.0% grants and incentives from donor agencies and other institutions. Conversely, the LCOE is significantly reduced as capital subsidies increase. This would help decision-makers ascertain the minimum cost at which electricity must be sold to achieve break-even over the project's lifetime.

The results in Table 8 have revealed that the utility-scale PV system is unattractive even at a 100.0% capital subsidy. In view of this, the study further modelled the system to include feed-in-tariff (FiT). This is based on the assumption that electricity produced by an independent power producer (IPP) or the government would generate revenues from electricity fed into the utility grid. Generally, FiT makes investing in renewable energy more secure. A FiT guarantees renewable energy producers' grid connection and government payment above market price. Structured payments span 15.0–20.0 years and are paid by energy users. FiT is phased out over time or when renewables reach a certain share of energy generation. Presently, Benin has no FiT, but the government encourages the development of large-scale projects. The current electricity tariff for households in Benin (the social slice) is about 86.0 FCFA/kWh (0.13 USD/kWh) (DCC, 2021). In this study, 3 different FiTs, including 0.05 USD/kWh, 0.10 USD/kWh, and 0.15 USD/kWh, similar to the ones used by other African countries, as shown in Table 9, are proposed to assess the economic resilience of the PV power plant.

The impact of FiT on NPV and annual lifecycle savings is shown in Fig. 5. It can be seen that NPV and annual lifecycle savings strongly depend on FiT. Thus, both NPV and annual lifecycle savings significantly increase as FiT increases. This signifies the positive impact of FiT on the project. Also, it can be observed from Fig. 5 that a FiT of 0.05 USD/kWh and 0.10 USD/kWh yields a negative NPV and annual lifecycle savings, though there is a significant reduction in NPV and annual lifecycle savings. Yet, the change in NPV and annual lifecycle savings for each installation site are comparable. On the other hand, the project starts to yield a positive NPV and annual lifecycle savings at the 0.15 USD/kWh FiT. The implication is that the project breaks even and becomes attractive for investment. Thus, stakeholders, decision-makers, and

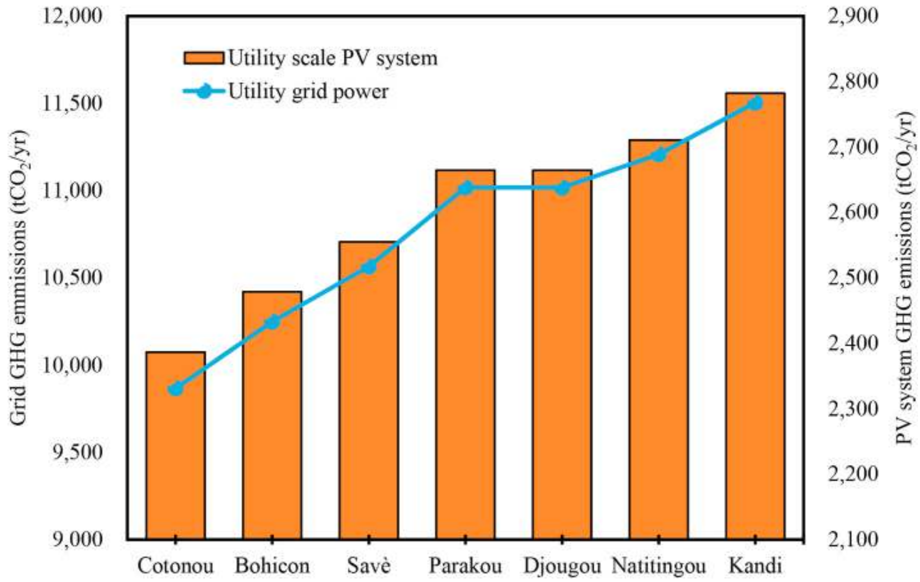

Fig. 7. Annual GHG emissions reduction.

Table 7
Summary of economic metric output for PV systems without revenues.

Site	Simple payback (yr)	NPV (million USD)	Annual lifecycle savings (million USD/yr)	LCOE (USD/kWh)
Cotonou	None	- 21.860	-1.550	0.128
Bohicon	None	- 21.860	-1.550	0.124
Savè	None	- 21.860	-1.550	0.120
Parakou	None	- 21.860	-1.550	0.115
Djougou	None	- 21.860	-1.550	0.115
Natitingou	None	- 21.860	-1.550	0.113
Kandi	None	- 21.860	-1.550	0.110

investors could profit substantially after investment.

The impact of the FiT on LCOE and the simple payback time (SPT) for each installation site are shown in Fig. 6. It can be gleaned from Fig. 6 that the LCOE is independent of variations in FiT. That cannot be said for SPT, which varies with FiT. The results show a positive SPT for each FiT at each installation site. The positive SPT indicates that the annual costs incurred are lower than the savings generated for each solar PV system. Also, it can be deduced that the estimated average SPT for the installation sites is 34.97 years, 15.56 years, and 10.02 years for 0.05 USD/kWh, 0.10 USD/kWh, and 0.15 USD/kWh, respectively. The results indicate that increasing the FiT for utility-scale grid-connected solar PV projects for project developers in Benin would yield a promising and attractive SPT. The average SPT of 15.56 years and 10.02 years for the installation sites in Benin are within the SPT range of 8.0 and 18.0 years recommended for assessing the economic viability of utility-scale grid-connected solar PV systems (Mensah et al., 2019). Based on this analysis, it can be said that the proposed 10.0 MW utility-scale grid-connected solar PV power plant could commence being economically viable at a FiT of 0.10 USD/kWh and above.

3.4. Greenhouse gas (GHG) emissions savings

There is a widespread misconception that solar modules produce zero emissions, but this is only true during electricity generation. Photovoltaic module emissions can be calculated when production, construction, maintenance, and decommissioning are considered. It is estimated that the average emissions from PV technologies are about 50.0 g CO_{2e}/kWh (NREL, 2012) and 98.3–149.3 g CO_{2e}/kWh (Mehedi et al., 2022). The GHG emissions from the solar PV system at the installation sites were estimated using Eq. (10). Benin's grid electricity mix stems from diesel fuel (71.0%) and hydropower (29.0%). Fuels used for grid electricity generation at transmission and distribution losses of

Table 9
Feed-in tariff for selected African countries (PV magazine, 2022).

Location	Capacity range	FiT	Operational term
Egypt	500 kW- 20 MW	0.136 USD/kWh	15.0 years
Kenya	500 kW–10 MW	0.12 USD/kWh	20.0 years
Algeria	>5 MW	0.074 USD/kWh (DZD10.48)	Price depends on the hours of operation per year
Tanzania	–	0.07 USD/kWh (152.54 TZS/kWh)	15.0 years

Table 8
Impact of capital subsidies on LCOE and NPV.

Cities	0% capital subsidy		25% capital subsidy		50% capital subsidy		75% capital subsidy		100% capital subsidy	
	NPV (Million USD)	LCOE (USD/kWh)	NPV (Million USD)	LCOE (USD/kWh)	NPV (Million USD)	LCOE (USD/kWh)	NPV (Million USD)	LCOE (USD/kWh)	NPV (Million USD)	LCOE (USD/kWh)
Cotonou	- 21.880	0.128	-17.261	0.101	-12.636	0.074	-8.011	0.047	- 3.386	0.020
Bohicon	- 21.880	0.124	-17.261	0.097	-12.636	0.071	-8.011	0.045	- 3.386	0.019
Savè	- 21.880	0.120	-17.261	0.095	-12.636	0.069	-8.011	0.044	- 3.386	0.019
Parakou	- 21.880	0.115	-17.261	0.091	-12.636	0.066	-8.011	0.042	- 3.386	0.018
Djougou	- 21.880	0.115	-17.261	0.091	-12.636	0.066	-8.011	0.042	- 3.386	0.018
Natitingou	- 21.88	0.113	-17.261	0.089	-12.636	0.065	-8.011	0.041	- 3.386	0.018
Kandi	- 21.88	0.110	-17.261	0.087	-12.636	0.064	-8.011	0.040	- 3.386	0.017

18.0% generate a GHG emission factor of about tCO_2 0.815/MWh for Benin. The GHG emission factor multiplies the total electricity generation to determine the emissions produced when the utility grid is used for electricity generation, as shown in Fig. 7. It can be observed that using the utility grid produces about 9868 tonnes to 11,504 tonnes of CO_2 emissions annually for the installation sites in Benin. On the other hand, the annual CO_2 emissions from PV systems are lower and range from 2386 tonnes to 2782 tonnes. This indicates that using the utility-scale PV plant for electricity generation at the installation sites saves about 76.0% of CO_2 emissions compared to the utility grid. Moreover, the average annual CO_2 savings (8170 tonnes) at the sites is equivalent to about 19,000 barrels of crude oil not consumed and about 8170 people reducing their energy use by 20.0% in Benin.

4. Conclusion

This study conducted the technical, economic, and emission analyses of a 10.0 MW utility-scale grid-tied solar PV power plant for seven sites in Benin. The study's key findings can be summarised as follows:

- The average electricity generation from the seven installation sites is about 13.22 GWh/yr. This could provide electricity to approximately 131,920 people (equivalent to 16,490 households using 8 people as a household size).
- The average capacity factor and performance ratio for the PV systems at the installation sites are about 15.1% and 67.3%, respectively.
- Without revenues and capital subsidies, the levelized cost of energy ranges from 0.110 USD/kWh to 0.125 USD/kWh.
- Based on Benin's estimated grid emission factor and the electricity available for grid export, about 8170 tonnes of CO_2 emissions could be saved every year after installation.
- Investing in utility-scale solar PV systems can be more economically viable with government support and infrastructure development. In addition, government support for capacity building in solar PV technologies (from design to production, utilising local resources) can expedite the commercialisation of solar PV technologies in Benin.
- The country must foster the development of policies that can accelerate the deployment of renewable energy projects and promote the use of new technologies for a cleaner and safer environment.
- The study results could guide Benin and other developing countries willing to implement a utility-scale grid-tied solar photovoltaic project. Future studies should use artificial intelligence optimization techniques to enhance the results.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgement

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Appendix A

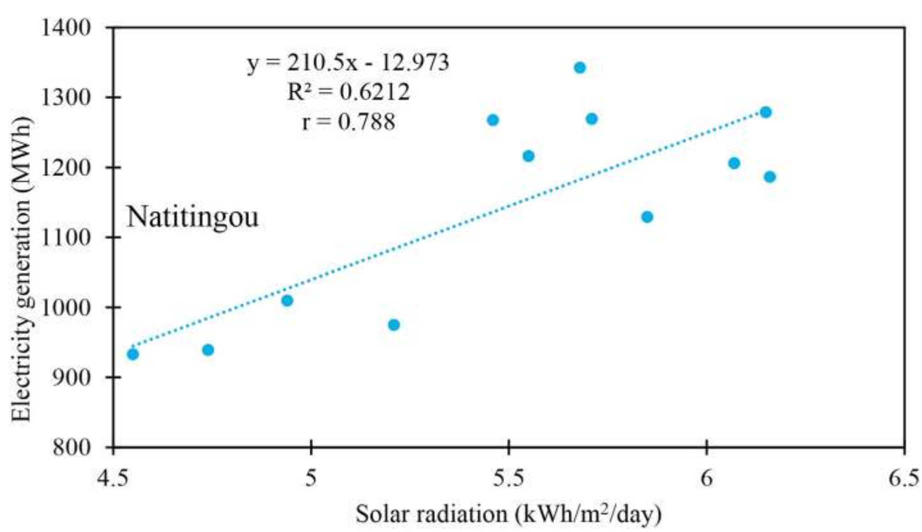

Fig. 1A. Correlation between monthly electricity generation and solar irradiation for Natitingou

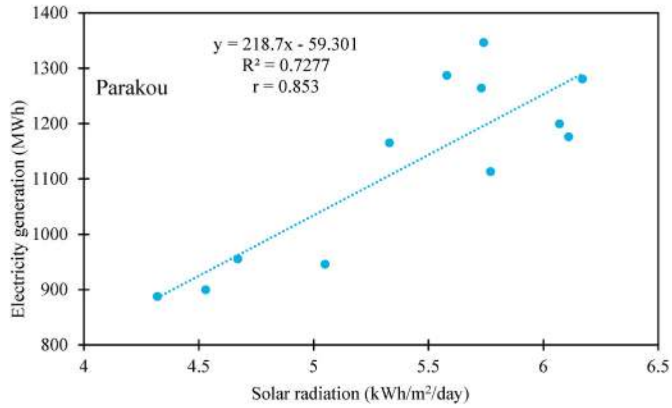

Fig. 2A. Correlation between monthly electricity generation and solar irradiation for Parakou

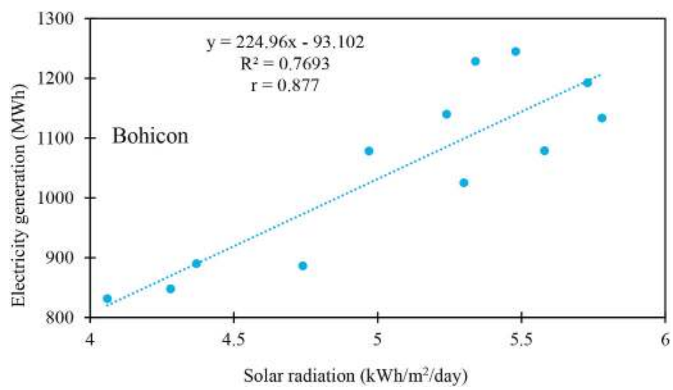

Fig. 3A. Correlation between monthly electricity generation and solar irradiation for Bohicon

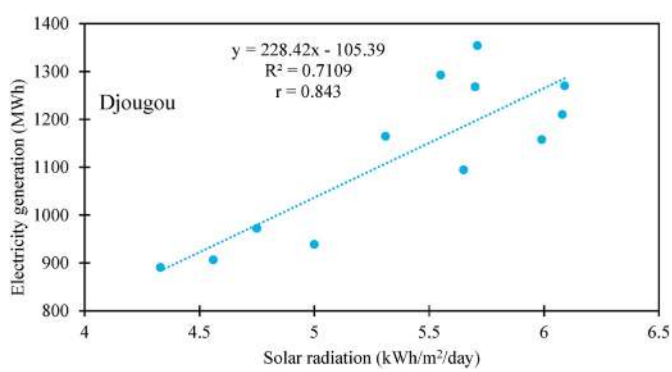

Fig. 4A. Correlation between monthly electricity generation and solar irradiation for Djougou

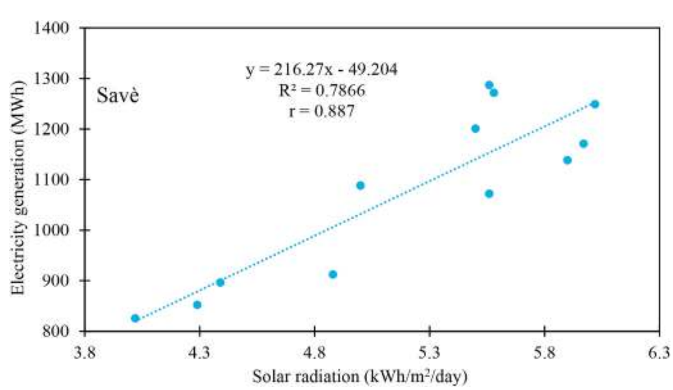

Fig. 5A. Correlation between monthly electricity generation and solar irradiation for Save

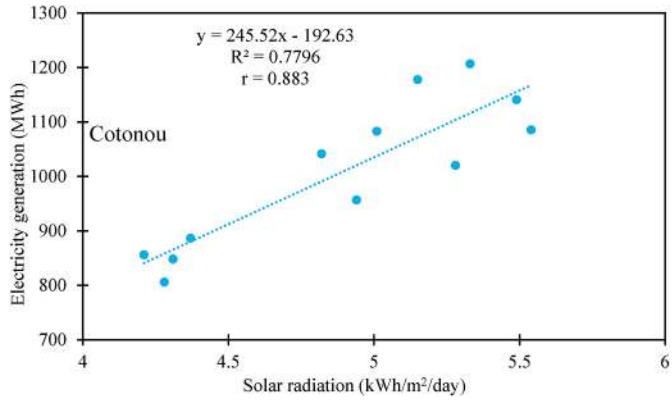

Fig. 6A. Correlation between monthly electricity generation and solar irradiation for Cotonou

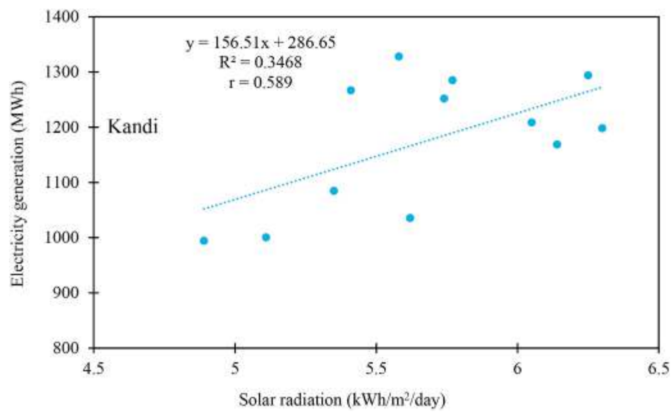

Fig. 7A. Correlation between monthly electricity generation and solar irradiation for Kandi

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