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# Assessment of solar energy potential and climatic effects on utility-scale photovoltaic power generation in The Gambia

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## ABSTRACT

The aim of the present study is to investigate the technical and economic viability of implementing photovoltaic (PV) systems in The Gambia by analyzing the availability of the solar resource, system performance, generation capacity, and economic viability. Long-term climate data from the NASA POWER database have been used to evaluate global horizontal irradiation, ambient temperature, rainfall, relative humidity, cloud cover, and wind speed at five locations in The Gambia. The analysis shows good potential for solar energy use, with annual GHI values ranging from 5.776 to 5.886 kWh/m<sup>2</sup>/day. Seasonal analysis revealed higher electricity generation during the dry season due to lower cloud cover, rainfall, and humidity. For 100% PV penetration, annual electricity generation ranges from 886.13 GWh in Soma to 913.87 GWh in Banjul. Correlation analysis shows that cloud cover ( $r = -0.976$ ) and precipitation ( $r = -0.944$ ) have the greatest negative impact on PV electricity production. System losses were also found to range from 21.34% to 22.80%, mainly due to variations in temperature and radiation. Moreover, the economic analyses indicated that the cost of electricity of proposed systems is within the range of 50.77-52.94 USD/MWh with a payback period of less than six years. This demonstrates the economic viability of utility-scale photovoltaic solar energy systems. The results show that the use of large-scale photovoltaic solar power systems can help provide a cost-effective alternative to fossil fuel-based electricity production by government institutions in The Gambia.

## 1. Introduction

Global energy demand has risen rapidly over the past few decades due to population growth, industrialization, urbanization, and technological progress [1]. The use of conventional fossil-fuel power generation has caused significant environmental problems, including carbon dioxide emissions, climate change, air pollution, and energy insecurity [2,3]. Due to the environmental advantages of solar PV panels, cost reductions, and ease of scalability, the adoption of solar power is increasing globally [4,5]. Solar energy is increasingly the fastest-growing renewable energy technology [6]. The International Renewable Energy Agency (IRENA) states that more than 1.4 TW of solar PV capacity was added globally [7]. This indicates the significance of solar energy in the global electricity market according to the International Renewable Energy Agency. Some developed nations, such as Germany, China, and the United

States, have managed to integrate their solar power systems into their national electricity networks to reduce the usage of non-renewable energy sources [8]. For instance, Germany has emerged as a leading country in the solar photovoltaic industry due to its renewable energy policies and solar power projects [9]. The shift towards solar power in Africa has similarly garnered greater interest due to the high levels of solar irradiation on the continent, along with rising electricity demand [10,11]. Several countries in Africa have undertaken large-scale solar projects to meet their energy needs and address shortages [12-14]. For instance, South Africa has been expanding its solar photovoltaic power plants through its Renewable Energy Independent Power Producer Procurement Program [15,16]. Although there is great potential for solar energy in The Gambia, the country's main source of electricity is fossil-fuel thermal power plants [17,18]. Besides, according to Marong et al. [19] and Manneh [20], there

are several problems in The Gambia's electricity sector, including heavy reliance on fossil fuel imports, rising electricity demand, insufficient generation capacity, relatively high generation costs, and an unstable supply. Moreover, statistics from the National Solar Energy Council (NAWEC) indicate that electricity production increased from 285,028 MWh in 2017 to 696,382 MWh in 2024, while electricity demand is expected to exceed 900,000 MWh in 2026 [21].

However, Gambia's location in the equatorial solar belt provides it with substantial solar radiation and potential for photovoltaic power generation [19, 22-29]. Several studies have evaluated the country's solar power potential. For instance, Marong et al. [19] developed a model for long-term electricity system optimization, based on the Strategic Alternatives to Energy Supply and its General Environmental Impacts (MESSAGE) model, to explore prospects for electricity production in the country. The results obtained showed that the application of solar photovoltaic power plants can reduce dependence on fossil fuels and greenhouse gas emissions. Ayua et al. [22] evaluated solar energy feasibility using the Angstrom model and newly designed analysis tools to support agricultural decision-making through solar energy assessment. The results revealed abundant, consistent solar energy in The Gambia that could be used for agriculture and other purposes. Kanteh Sakiliba et al. [23] analyzed stand-alone residential solar energy systems in The Gambia. The authors concluded that stand-alone solar photovoltaic systems are a more efficient and cost-effective alternative to grid energy. Sawaneh [24] analyzed the process of transitioning to clean energy in Gambia. The authors concluded that the adoption of renewable energy is constrained by institutional and infrastructure barriers, despite the significant potential in this area. Ayua and Camara [25] evaluated the improvement in photovoltaic cell system performance by varying tilt angles and orientations. The results showed that the appropriate configuration can increase solar energy production in the Gambian environment. Hydera et al. [26] studied the performance of a 120 kW off-grid solar power system in Nyamanari village. The system has been shown to work well, providing evidence that photovoltaic cell technology is technically reliable in local climatic conditions. Obeng-Darko [27] studied the regulatory and political aspects of renewable energy development. The authors concluded that the lack of governance and policies is the main obstacle to the widespread deployment of renewable energy. Sakiliba et al. [28] discussed the applications of photovoltaic solar energy in homes and demonstrated its economic viability and ability to provide decentralized electricity. Sowe et al. [29] conducted a technical and economic feasibility study of photovoltaic power plant projects to supply electricity to rural areas and demonstrated their economic viability. Moreover, increasing the use of renewable energy sources, particularly photovoltaic systems, would help reduce carbon emissions and fossil fuel consumption, thereby promoting future energy sustainability, according to Bass and Lopez-Agüera [30]. It should be noted that the authors adopted a long-term optimization methodology using the Open-Source Energy Modeling System (OSeMOSYS) to analyze energy transition alternatives in The Gambia through 2050.

Based on the above, previous studies have focused on optimizing the national energy system, renewable energy policies, evaluating solar resources, and applying off-grid photovoltaics. Nevertheless, none of the studies evaluate the solar resources, the impact of weather conditions on PV performance, or the sizing of PV systems at the country level. Accordingly, the existence of such gaps in studies makes it difficult to plan for the country's energy future. There is an urgent need to establish a solid research foundation to enable policymakers and energy planners to determine whether large-scale solar photovoltaic power can

successfully replace a significant portion of electricity generated from fossil fuels in The Gambia. Thus, the objectives of this research work are to (1) estimate the solar energy potential and its geographical distribution at specific locations in The Gambia using meteorological data from NASA's POWER dataset; (2) analyze the performance of large-scale photovoltaic solar power installations in terms of the effects of important climate variables, calculate photovoltaic power capacity requirements, and evaluate different power generation scenarios of 50%, 75%, and 100% demand replacement; (3) evaluate the feasibility of the economic and environmental impacts of installing photovoltaic solar power plants on a large scale, using technical and economic studies and an assessment of greenhouse gas emission reduction; and (4) provide scientific background and policy recommendations to promote sustainable energy development and facilitate the low-carbon transition of the electricity sector in the country.

2. Materials and methods

2.1 Study area

This research is conducted in The Gambia, a West African country located along the Gambia River between 13°N and 14°N latitude and 13°W and 17°W longitude. The country is known for its tropical climate, characterized by dry and wet seasons, abundant sunshine, and long periods of continuous sunshine, making it optimal for photovoltaic energy development. In this study, the five representative sites selected to study solar energy potential in the country's various climatic and geographical regions are shown in Table 1. This is because the selected sites have diverse climatic conditions and varying electrical load requirements. The five sites selected for the solar energy potential assessment include various climates. Five selected sites were used to collect data across different geographical and climatic conditions, so they would exhibit distinct electricity usage patterns and meteorological conditions. The selection of five study sites will provide a broad spatial range for assessing differences in regional climates in solar radiation, temperature, wind speed, humidity, cloud cover, and other climatic variables that affect photovoltaic cell output. Climatic data for all selected sites were obtained using the NASA Power Database.

Table 1. Information about the selected locations

Location	Latitude	Longitude	Characteristics
Banjul	13.45° N	16.58° W	Coastal capital city
Brikama	13.27° N	16.65° W	High-population urban area
Farafenni	13.57° N	15.60° W	North Bank region
Soma	13.43° N	15.53° W	Central strategic location
Basse	13.31° N	14.22° W	Eastern inland region

The electricity sector in The Gambia has seen significant expansion over the past ten years due to the country's growing population, urbanization, and economic development. National Water and Electricity Corporation (NAWEC) controls the country's electricity grid, which is responsible for generating, transmitting, and distributing power nationwide. The main feature of the energy sector in Gambia is the heavy reliance on thermal power generation. Electricity production in The Gambia has grown steadily year after year due to rising national demand. Based on Figure 1 from the National Electric Power Authority, the country's electricity production grew from 285,028 MWh in 2017 to 696,382 MWh in 2024, with projections indicating it will reach 904,146 MWh in 2026. This is more than three times the amount of electricity produced in less than a decade.

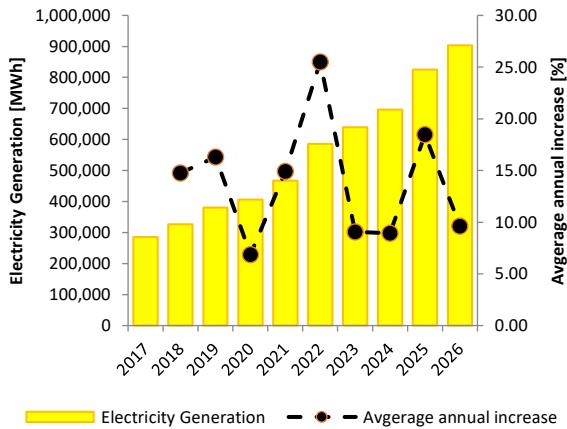


Figure 1. Electricity generation growth (2017–2026)

2.2 NASA POWER reanalysis dataset

Climate and weather have the greatest influence on human endeavors such as agriculture and industry [31]. Despite significant advancements in meteorological satellites and ground-based stations over the past few decades, many countries worldwide still lack adequate meteorological data, particularly in developing nations. Because of this, reanalysis and gridding of meteorological data produced by atmospheric models are among the best ways to provide the needed meteorological data where it is lacking. Meteorological data generated by atmospheric reanalysis combines observational and forecast data [32]. There are numerous reanalysis datasets available across the globe for long historical periods [33], such as the Modern-Era Retrospective Analysis for Research and Applications (MERRA) by the National Aeronautics and Space Administration and the NASA Prediction of Worldwide Energy Resource (NASA POWER) from the Goddard Earth Observing System (GEOS) reanalysis. NASA has supported the use of satellite data to estimate parameters such as the amount of energy emitted to Earth, which is crucial for climate science studies [34]. According to NASA POWER Data Access Services (<https://power.larc.nasa.gov/docs/v1/>), this data is provided at the single-point, regional, and global levels, with daily, annual, and climatological average periods. In this case, a single endpoint provides a location-dependent data series (i.e., a single latitude and longitude). At the same time, the regional endpoint provides time series for the area defined by the latitude-longitude bounding box. On the other hand, the global endpoint provides a long-term climate data series for the entire Earth. These meteorological variables include the average of near-surface air temperature (maximum, minimum, mean, and dew point), relative humidity, precipitation, solar radiation, and wind speed and direction. This data source can be used in a variety of applications, including climate change applications and crop models [35].

The reliability of NASA Power data has been confirmed by numerous studies conducted on climates similar to those of West Africa. For instance, Jed et al. [36] compared NASA POWER solar irradiance data with ground measurements at four stations in Mauritania and Algeria. The results indicated that NASA POWER data could be used reliably to assess solar energy projects where measured data is unavailable. Sayago et al. [37] compared solar radiation values from NASA POWER with observed data from 31 stations in Spain. They concluded that NASA POWER can provide an accurate estimate of solar radiation for renewable energy applications and the design of photovoltaic systems. Monteiro et al. [38] reported that solar radiation is among the most accurately estimated variables in

NASA POWER, with R<sup>2</sup> values ranging from 0.91 to 0.97 and a normalized RMSE of no more than 16%. Therefore, the country’s solar energy potential was analyzed using NASA POWER data collected from 2001 to 2025.

2.3 PV system sizing

Grid-connected photovoltaic power stations are being developed to meet the country’s daytime energy needs. Therefore, the value of energy supplied to the grid by the photovoltaic power station ( $E_{inj}$ ) must be higher than the value of energy withdrawn from the grid ( $E_{abs}$ ) [39].

$$E_{inj} > E_{abs} \tag{1}$$

In general, a grid-connected PV system can be composed of the following parts: PV modules, inverters, a distribution controller, and a load. Previous studies [40,41] have indicated that the use of grid-connected photovoltaic solar power systems helps reduce energy consumption, minimize losses in distribution network capacity, and modernize transmission and distribution processes. The developed system is independent of the battery type and capacity [41]. Moreover, the requested solar capacity ( $P_{PV}$ ) can be estimated using Eq (2) according to Maammour et al. [42].

$$P_{PV} = \frac{E_{demand} P_i}{SR_{Av} f_{PV} \eta_{inv}} \tag{2}$$

where  $P_i$  is the solar radiation at STC in kW/m<sup>2</sup>,  $SR_{Av}$  is the global solar radiation (kWh/m<sup>2</sup>/d),  $f_{PV}$  is the PV derating factor,  $E_{demand}$  is the annual power consumption in kWh/year, and  $\eta_{inv}$  is the inverter yield.

2.4 Selection of PV module and inverter

PV cell modules can be divided into different types in the market, including monocrystalline silicon, polycrystalline silicon, and amorphous silicon modules. In this regard, it is necessary to consider the cell type, system cost, warranties, size, and wattage when selecting a photovoltaic solar module [43]. Furthermore, Balu and Shaganchua [44] indicated that the US Photovoltaic Testing (PTC) conditions and the type of materials used are vital factors in the selection of solar panels [45]. In addition, El-Bayeh et al. [46] suggested that the characteristics of the photovoltaic cell module (module size, power rate, price, and efficiency) constitute one of the critical factors for the design of a photovoltaic cell system. Furthermore, Sasikumar and Ayyappan [47] identified the energy rate and unit weight as the two most important factors.

In this study, high-efficiency TOPCon bifacial photovoltaic modules rated at 700-720 watts were selected for the proposed solar power plants. This is because these units have an efficiency greater than 22%, a lower temperature coefficient, and a higher biphasic power gain factor. These features make the selected units highly desirable for application in a hot tropical climate such as that of Gambia. The specification of the selected solar panel (Trina Vertex N 720W TOPCon Module) is provided in Ref [48]. In addition, an inverter is an electrical component that converts the direct current generated by the PV system into alternating current supplied to the grid. There are various types of inverters available in the market. Factors such as AC output power, DC-AC conversion efficiency, and cost are important when choosing the best inverter. Utility-scale inverters with a capacity of 350 kW were chosen for the proposed solar PV systems owing to their high DC-AC conversion efficiencies, low balance-of-system costs, and suitability for utility-scale grid-connected systems. The chosen inverters have efficiencies approaching 99%, several MPP tracking channels, and the ability to integrate with 1500-volt PV systems. The specification of the selected inverter (Solis S6-GU350K-EHV 350kW Inverter) can be found in Ref [49].

### 2.5 Estimating solar PV energy output

The monthly energy production (*EP*) of a photovoltaic solar energy system is calculated by taking into account criteria such as the number of hours of sunshine per month at the installation site, the system capacity, and the power reduction factor. The estimated monthly energy production (in kilowatt-hours) of a photovoltaic solar energy system can be calculated mathematically using Eq (3) [50].

$$EP = N_d \times f_m \times \frac{SR_{Av}}{1 \text{ kW/m}^2} \times P_{IC} \quad (3)$$

where  $f_m$  is the average monthly derate factor (assumed to be equal to 0.8 [51,52],  $N_d$  is the number of days in the month,  $SR_{Av}$  is solar radiation on the plane of the solar PV array in kWh/m<sup>2</sup>/day, and  $P_{IC}$  is solar PV installed capacity in kW.

### 2.6 Performance parameters

A selection of factors is considered when evaluating the energy performance of a solar power plant, including site location, system losses, angle-of-incidence losses, and temperature- and irradiance-related losses. The performance evaluation was conducted using the following technical criteria:

**Capacity utilization factor (CUF):** CUF is regarded as a crucial characteristic for the functioning of solar systems. CUF is one of the performance factors identified for yearly energy production. CUF is defined as the ratio of the AC energy generated (final output) by the photovoltaic system over a year to the maximum achievable energy generation over a year under ideal operating conditions [53]. Eq (4) displays the expression for calculating CUF.

$$CUF = \frac{EP}{\text{Installed Capacity} \times N_d \times 24} \quad (4)$$

**Effect of angle of incidence:** The photocurrent is produced when the sun's radiant light energy strikes the photovoltaic module's surface. A photovoltaic module's surface will always be angled away from the normal when sunlight strikes it. The reflectivity of radiant energy increases at the module surface, which is not responsible for producing heat or photocurrent. Hence, there will be considerable losses in the photovoltaic system's output energy. Therefore, it is recommended to account for the angle of incidence when studying the PV system's performance [53].

**Spectral effects:** The solar radiation spectrum of the photovoltaic modules must be considered when evaluating performance parameters. This is because the conversion efficiency of each photovoltaic module in the PV system depends on the solar spectrum. Thus, the output of photovoltaic modules in a PV system will differ under varying sunlight spectra compared with the standard spectrum at the site where the PV power plants are installed. Therefore, it becomes essential to determine the effective spectrum during the evaluation process. According to the IEC-60904-3 standard [54], the spectrum of the light is defined on the module side under the standard testing conditions.

**Effect of module temperature:** PV system performance depends on module temperature. As the day progresses, the temperature of the modules increases with increasing input irradiance. The temperature of the modules will be greater than that of the ambient environment. Therefore, this becomes another critical variable that must be considered in the analysis [53].

### 2.7 Economic analysis

To develop a solar photovoltaic (PV) power plant project economically at the utility level, it is important to optimize electricity generation while minimizing implementation and operational costs. However, the economic viability of such solar photovoltaic projects depends largely on the cost of photovoltaic modules, inverters, and installations, as well as operating and maintenance costs. Given the dependence of solar energy

generation on the area's climatic and radiation conditions, selecting suitable technologies and configurations for each project location is crucial. Energy cost calculations for solar PV systems have been well explored previously, with various techniques for evaluating system economics. For this study, the numerical technique used to assess the economic viability of the solar PV projects proposed here is the present value cost (PVC). This approach was selected because there were three main reasons behind this [55-57]:

- From an economic perspective, the approach provides the most realistic and dynamic assessment.
- The difference between costs and benefits does not depend on the moment in time when payment occurs.
- Due to reason ii), the deduction of the discount (interest charge accumulated over time) can be made.

Thus, the PVC method is formulated by Eq (5) [55].

$$PVC = I + \sum_{n=1}^N \frac{C_n}{(1+r)^n} \quad (5)$$

where  $C_n$  is the annual costs,  $I$  is the initial investment,  $N$  is the period of years (25 years) [56] and  $r$  is the discount rate.

In addition, the Levelized Cost of Electricity (LCOE) is used to estimate the cost per kWh produced by the solar plant, as given by Eq. (6) [57].

$$LCOE = \frac{PVC}{\text{Annual Energy Production} \times t} \quad (6)$$

Besides, the payback period (*PBP*) is a financial metric that helps determine the time required to recover the investment cost through the income it generates. It measures the time required for the investment to reach a breakeven point. The *PBP* is a tool that easily measures the time duration taken to recover an investment. The *PBP* period can be calculated using Eq (7).

$$PBP = \frac{\text{Investment cost}}{\text{Annual saving}} \quad (7)$$

## 3. Results

### 3.1 Climate parameters characteristics

The global horizontal irradiance (GHI) across different regions of The Gambia indicates that the country has strong year-round solar potential, as shown in Figure 2. This is a key parameter used when analyzing the efficiency of PV power generation. The annual mean GHI values range from 5.776 to 5.886 kWh/m<sup>2</sup>/day, with relatively minimal spatial variability. For instance, the Basse and Soma areas experience the highest annual mean GHI, at 5.886 kWh/m<sup>2</sup>/day, compared to other regions such as Banjul and Brikama, which have an annual mean of 5.776 kWh/m<sup>2</sup>/day. The other region with a medium annual mean value is Farafenni, at 5.849 kWh/m<sup>2</sup>/day. This implies that inland locations receive relatively high levels of irradiance due to less maritime cloud cover and atmospheric moisture. In terms of seasonal variation, all selected areas recorded relatively higher GHI values in the dry season than in the rainy season. Dry-season GHI values ranged from 5.946 to 5.993 kWh/m<sup>2</sup>/day, whereas rainy-season values were the lowest, at 5.512 and 5.740 kWh/m<sup>2</sup>/day. The lower GHI values were largely influenced by increased cloud cover, atmospheric moisture, and precipitation. The Basse and Soma regions continue to have the highest dry-season GHI, at 5.993 kWh/m<sup>2</sup>/day, indicating good solar performance during periods of low cloud cover. On the other hand, Banjul and Brikama record the lowest rainy-season figures of 5.512 kWh/m<sup>2</sup>/day, probably because of their proximity to the Atlantic coastline. Additionally, Figure 3 shows the average air temperatures (AT) across different regions of The Gambia, indicating that the country has consistently warm tropical weather year-round, with average annual temperatures ranging from 25.27°C to 28.30°C. Areas further inland from the coast, such as

Bass and Soma, record higher temperatures than coastal areas, which are slightly cooler due to the influence of the Atlantic Ocean. Considering seasonal temperature variations across different regions of The Gambia, we find that temperatures tend to rise during the dry seasons in the interior due to increased solar radiation, whereas seasonal temperature variations in coastal areas are less pronounced due to higher humidity and the influence of the ocean. These temperature patterns are vital for studying solar energy because air temperatures affect the efficiency of photovoltaic modules.

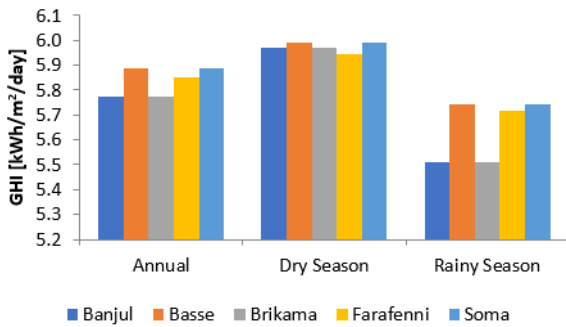


Figure 2. Mean value of GHI for various regions in the Gambia during the period of 2001-2025

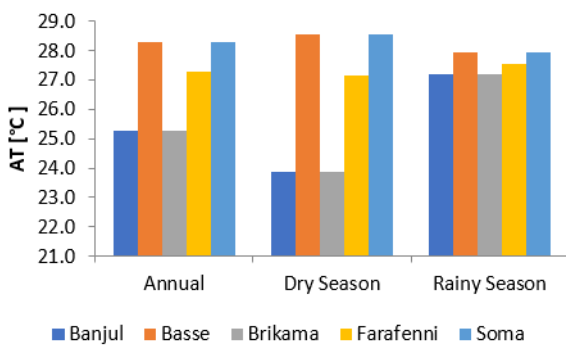


Figure 3. Mean value of AT for various regions in the Gambia during the period of 2001-2025

Moreover, the annual average wind speed (WS) data for various parts of The Gambia are consistent with the country's wind energy potential, as illustrated in Figure 4. The annual average wind speeds range from 2.40 m/s to 3.26 m/s, with the highest in the coastal regions of Banjul and Brikama, and the lowest in inland regions such as Basse, Soma, and Farafenni. There is an observed seasonal variation, with higher wind speeds in the dry season than in the rainy season. There is an observed increase in wind speed during the dry seasons due to stronger atmospheric circulation and reduced air moisture. The high wind speeds in coastal areas result from the sea breeze effect of the Atlantic Ocean. The significance of the wind speed pattern lies in planning the use of renewable energy sources. High wind speeds are crucial for efficient and effective wind electricity generation. Furthermore, the presence of wind helps cool photovoltaic panels, hence improving their efficiency. In general, humidity is a key climatic parameter in solar energy research, as high humidity can reduce solar radiation intensity and PV module efficiency. Therefore, its knowledge is crucial in assessing solar energy and designing renewable energy systems in The Gambia. The seasonal variation in average relative humidity (RH) values (Figure 5) for different locations in The Gambia is clearly visible and depends on rainfall and proximity to the Atlantic Ocean.

Annual mean humidity ranges from 49.89% to 73.06%, with coastal cities, including Banjul and Brikama, registering higher mean humidity than other parts of the country, where dry continental winds prevail. It is found that relative humidity increases significantly during the rainy season, with average values exceeding 76%, due to high rainfall, cloud cover, and higher overall atmospheric humidity. During the dry season, however, the relative humidity is lower, especially inland, so it will not have a major influence on cloud coverage and solar radiation intensity.

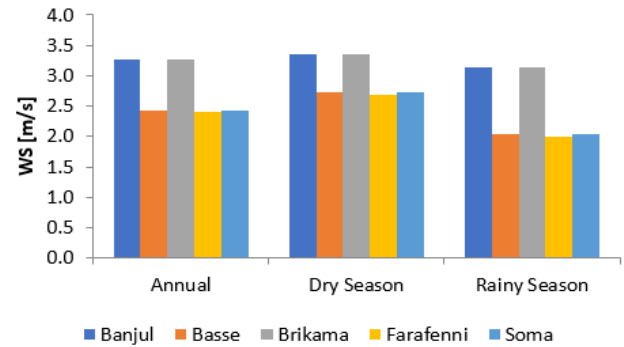


Figure 4. Mean value of WS for various regions in the Gambia during the period of 2001-2025

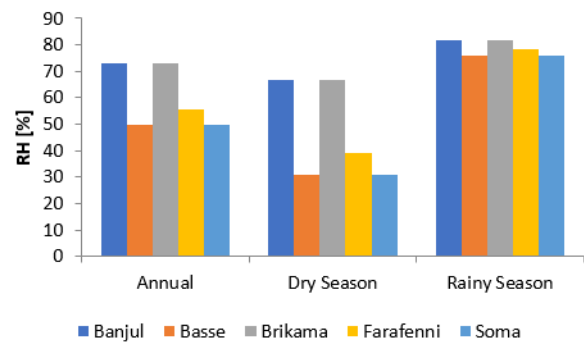


Figure 5. Mean value of RH for various regions in the Gambia during the period of 2001-2025

Additionally, the cloud cover (cloud amount (CM)) plays a vital role in assessing the solar power of any region since the solar irradiance depends on the amount of cloud. Higher cloud cover reduces irradiance and PV electricity generation. The mean annual cloud cover across various regions in The Gambia indicates considerable cloud cover in most seasons, as shown in Figure 6. Based on the findings, there is usually a high annual mean cloud cover ranging from 45.63% to 50.00% across different regions of The Gambia. Farafenni has a considerably higher annual cloud cover than Banjul and Brikama, which have relatively low cloud cover. Seasonal differences in cloud cover are evident, with the dry season having very few clouds. The number of clouds recorded is much higher during the rainy season due to increased moisture, precipitation, and an unstable atmosphere. All regions experience more than 59% cloud cover during the rainy season.

Generally, average rainfall (R) is considered a climatic variable in the analysis of solar energy in the region, since higher rainfall implies greater cloud cover and lower radiation levels, resulting in reduced electricity production by photovoltaic cells. Rainfall helps remove dust that may settle on solar panels. Seasonal variability in average rainfall across various regions in The Gambia is evident, with most rainfall occurring during the

rainy season. Average rainfall varies across the regions between 824 mm and 906 mm, with Farafenni reporting higher rainfall and Banjul and Brikama reporting relatively low rainfall, as shown in Figure 7. During the dry season, rainfall is negligible across all regions, with average amounts of about 11 to 26 mm, indicating dry, clear atmospheric conditions. On the contrary, during the rainy season, rainfall contributes almost entirely to annual rainfall totals, with amounts exceeding 798 mm in all regions owing to the effects of the West African monsoon.

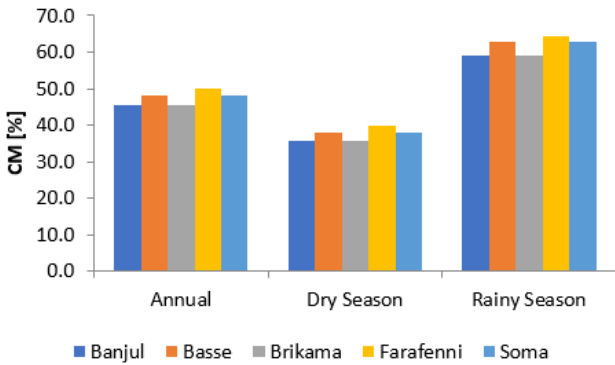


Figure 6. Mean value of CM for various regions in the Gambia during the period of 2001-2025

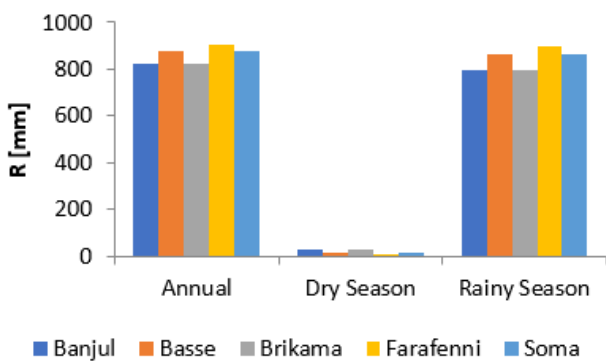


Figure 7. Value of R for various regions in the Gambia during the period of 2001-2025

### 3.2 Energy Production from the developed PV plants

The assessment of photovoltaic energy across various regions in The Gambia demonstrates the country's great potential for large-scale solar energy production. This was achieved by using the Global Horizontal Solar Irradiance Minimum (GHI) of 5.028 kWh/m<sup>2</sup>/day found for all regions, which is considered the lowest solar irradiance condition. This will help ensure that all estimates made in the analysis are based on actual calculations of solar radiation. The annual electricity consumption by government stations is 824,905 MWh (Figure 1), while the proposed photovoltaic power production is 529 MWh (estimated using Eq (2)). Three penetration levels were calculated to assess the contribution of photovoltaic solar power systems to the government's electricity demand, as shown in Table 2.

Generally, the optimal values of slope angle and azimuth angle are essential parameters that ensure the highest yield from photovoltaic technology in The Gambia. It has been observed that the optimal slope angle across all regions is approximately 16°. This value is similar to the country's latitude. Thus, the optimum slope angle is ideal for capturing maximum sunlight and ensuring efficient solar power production. Furthermore, the optimal

azimuth angles range from -4° to 0°, indicating that the solar modules should be oriented almost due south, with slight eastward or westward adjustments depending on the region. For instance, in Banjul and Basse, the optimum azimuth angle is -4°; in Brikama and Farafenni, it is -2°; and in Soma, it is 0°. Scenario 1 (PV contribution of 50%) yields an average annual estimate of PV energy produced ranging from 442.2 GWh in Soma to 456.1 GWh in Banjul. Basse is expected to produce about 454.6 GWh, while Brikama and Farafenni are expected to produce approximately 448.8 GWh and 445.4 GWh, respectively. It can be seen that there is little variation in PV energy output across regions; however, coastal cities like Banjul have a slight edge in electricity generation because they receive adequate solar radiation. It has been estimated that PV power generation peaks in March to May because there is ample solar radiation and fewer clouds. Banjul receives approximately 45.9 GWh of solar power in March, but less in July and August when it rains.

Table 2. Energy production value in GWh from the proposed systems (DS = Dry Season; RS = Rainy Season)

Month	Banjul	Basse	Brikama	Farafenni	Soma
Scenario 1 (PV contribution of 50%; Installed capacity = 264MW )					
Jan	41.7	41.4	41.4	41.5	41.5
Feb	39.7	39.4	39.3	39.3	39.2
Mar	45.9	45.6	45.4	45.3	44.9
Apr	43.0	42.8	42.3	42.1	41.6
May	41.1	40.9	40.6	40.3	39.9
Jun	35.5	35.4	35.0	34.3	34.0
Jul	30.5	30.6	29.4	28.8	28.1
Aug	28.6	28.7	27.3	26.9	26.7
Sep	30.9	31.0	29.6	29.2	28.9
Oct	38.5	38.5	38.1	37.4	37.2
Nov	40.1	40.0	40.0	39.9	39.8
Dec	40.6	40.3	40.3	40.4	40.5
Annual	456.1	454.6	448.8	445.4	442.2
DS	292.0	290.4	289.3	288.9	287.4
RS	164.0	164.2	159.4	156.6	154.9
Scenario 2 (PV contribution of 75%; Installed capacity = 397MW )					
Jan	62.7	62.2	62.3	62.5	62.4
Feb	59.6	59.2	59.1	59.1	58.9
Mar	69.0	68.6	68.3	68.1	67.5
Apr	64.7	64.4	63.7	63.4	62.6
May	61.8	61.6	61.1	60.6	60.0
Jun	53.4	53.3	52.7	51.6	51.1
Jul	45.9	46.0	44.2	43.2	42.3
Aug	43.0	43.2	41.1	40.5	40.1
Sep	46.5	46.6	44.6	43.9	43.5
Oct	57.9	57.9	57.2	56.3	56.0
Nov	60.3	60.1	60.1	60.0	59.8
Dec	61.1	60.6	60.6	60.7	60.9
Annual	685.8	683.6	674.8	669.8	665.0
DS	439.1	436.8	435.1	434.4	432.1
RS	246.7	246.9	239.7	235.5	232.9
Scenario 3 (PV contribution of 100%; Installed capacity = 529MW )					
Jan	83.6	82.9	83.0	83.3	83.2
Feb	79.5	78.9	78.8	78.8	78.5
Mar	91.9	91.4	91.0	90.8	90.0
Apr	86.2	85.8	84.8	84.5	83.4
May	82.3	82.0	81.4	80.7	80.0
Jun	71.1	71.0	70.2	68.8	68.1
Jul	61.2	61.3	58.8	57.6	56.3
Aug	57.4	57.5	54.7	53.9	53.4
Sep	61.9	62.0	59.4	58.5	57.9
Oct	77.1	77.1	76.3	75.0	74.6
Nov	80.4	80.1	80.1	79.9	79.7
Dec	81.4	80.7	80.8	80.9	81.1
Annual	913.9	910.9	899.2	892.6	886.1
DS	585.2	582.0	579.8	578.8	575.8
RS	328.7	328.9	319.4	313.8	310.3

In Scenario 2 (PV at 75%), the annual energy output of the PV systems increases significantly, ranging from 665.0 GWh/year in Soma to 685.8 GWh/year in Banjul. This scenario demonstrates the PV system's ability to supply the majority of the electricity required by government installations. Similar trends in monthly production are observed compared to Scenario 1, with high production rates in the dry season and low production rates in the rainy season. Dry-season energy production exceeds 430.0 GWh across all sites, whereas rainy-season energy production declines due to atmospheric conditions that reduce solar irradiation. Scenario 3 (100% PV contribution) corresponds to full-scale operation of the suggested PV facilities. Here, the annual energy generation capacity goes up from 886.1 GWh in Soma to 913.9 GWh in Banjul. The figures include 910.92 GWh in Basse, 899.2 GWh in Brikama, and 892.6 GWh in Farafenni. PV installations could generate enough electricity to cover part of the demand at government plants.

The energy generation capacity peaks in March, April, and May because the sun is stronger during these months and weather conditions are generally favorable. In this case, energy generation in Banjul reaches a maximum of over 91.9 GWh in March. This can be observed in seasonal analysis, as dry seasons produce more electricity than wet seasons across all scenarios and regions. For example, in Scenario 3, dry-season production in Banjul is about 585.2 GWh, whereas wet-season production is 328.7 GWh. The same trend applies to all other regions. This is mainly because in dry seasons there is less cloud cover, less rainfall, and lower relative humidity than in rainy seasons. A clear sky during dry seasons allows more solar radiation to reach PV modules, thereby producing more electricity. The region-wise variance of energy produced from PVs is directly linked to the climatic factors examined earlier in the study. Lower cloud cover and lower relative humidity generally lead to slightly higher PV output. Coastal regions have somewhat lower temperatures because they are located near oceans and seas. This results in higher module efficiency, as high temperatures negatively impact PV performance. Similarly, high solar irradiance and ambient temperatures are expected in inland regions such as Basse and Soma.

The results clearly indicate that The Gambia's solar energy potential is excellent and ideal for both large-scale and institutional PV use. High PV generation across all studied regions makes it possible to integrate solar energy into the country's electricity grid. The introduction of such a system would offer several advantages, including reduced reliance on fossil fuels, increased national energy security, lower greenhouse gas emissions, lower electricity costs, and the implementation of sustainable development principles. Moreover, the analysis shows that even at low irradiation levels, a considerable amount of electricity can be produced year-round. It demonstrates the significance of investing in renewable energy sources for the country, given the growing electricity demand.

**3.3 Performance of PV system**

From Figure 8, PV power systems exhibit stability and good performance throughout the year across all regions. The average capacity factor for the year varies slightly from 19.1% in Soma to 19.7% in Banjul and Basse. The highest capacity factors are achieved in January through April because solar radiation is high and cloud cover is low. The lowest capacity factors, however, are achieved during July and August. The capacity factor during the dry season is about 21.4%-21.8%, while that in the rainy season drops to 16.0%-16.9%. The seasonal drop in PV electricity production explains why energy production is significantly higher in the dry season across all scenarios. Places like Banjul and Basse, with relatively high-capacity factors, also produce more energy annually than Soma and Farafenni. The capacity factor

remains nearly the same across Scenarios 1 (50%), 2 (75%), and 3 (100%). The capacity factor primarily depends on the availability of solar energy and the system's operational parameters, rather than on PV capacity. An increase in PV size results in more electricity being produced, but the ratio of energy actually produced to the energy that could be produced remains unchanged. These findings are crucial because the capacity factor is a key measure of PV system performance. An annual capacity factor near 20% means that The Gambia has enormous potential for solar energy utilization to generate electricity.

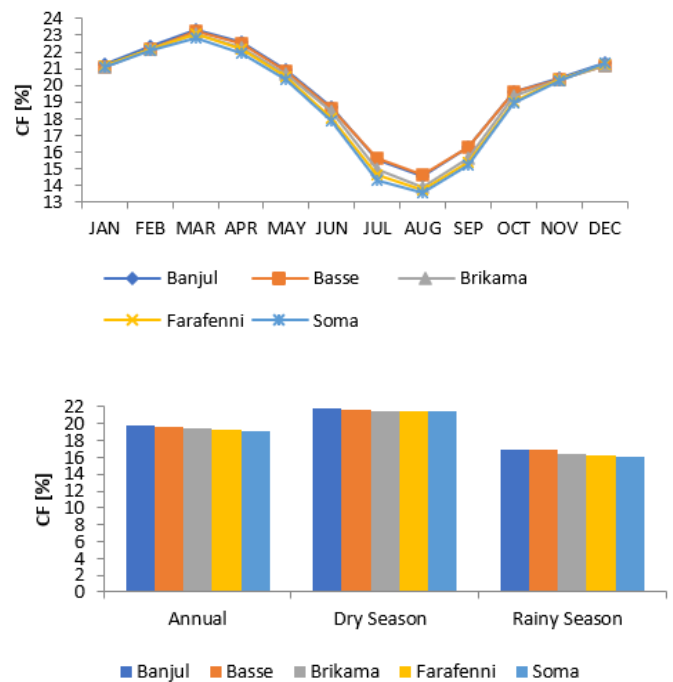


Figure 8. Monthly and annual value of CF for various regions in The Gambia

**3.4 Correlation analysis**

Correlation analysis of photovoltaic energy production and climatic factors in The Gambia is important because it helps clarify the relationship between environmental characteristics and solar energy generation. As indicated in Table 3, the results reveal both positive and negative correlations between the analyzed factors, whereas statistical correlations (0.01 level) prove that climate has a considerable impact on the operation of photovoltaic power systems. Global horizontal irradiation is positively correlated with energy production ( $r = 0.435$ ). As for air temperature, global horizontal irradiation shows a strong positive correlation ( $r = 0.715, p < 0.01$ ). This proves that when the Sun's radiation is intense enough, the air becomes warmer. In addition, global horizontal irradiation is negatively correlated with relative humidity, precipitation, and cloud cover. AT was found to have a slight negative correlation with energy production ( $r = -0.173$ ). This implies that very high temperatures tend to slightly decrease energy output because, while AT increases solar irradiance, it also increases the resistance of the semiconductors used in PV cells. WS had a medium positive correlation with energy production ( $r = 0.410$ ). This means that energy production tends to be higher when wind speeds are high, as WS cools solar panels. WS also shows a strong negative correlation with RH ( $r = -0.724, p < 0.01$ ), indicating that drier air tends to have stronger winds. Moreover, RH shows a very strong negative relationship with energy production ( $r = -0.868, p < 0.01$ ).

**Table 3.** Pearson correlation illustrating the relationships among GHI, AT, WS, RH, R, CM, and energy production (EP)

Variable	Correlation statistics	Variable						
		GHI	AT	WS	RH	R	CM	EP
GHI	Pearson Correlation	1						
	Sig. (2-tailed)							
AT	Pearson Correlation	.715**	1					
	Sig. (2-tailed)	0.009						
WS	Pearson Correlation	0.553	0.085	1				
	Sig. (2-tailed)	0.062	0.794					
RH	Pearson Correlation	-0.382	0.314	-.724**	1			
	Sig. (2-tailed)	0.221	0.321	0.008				
R	Pearson Correlation	-0.346	0.178	-0.42	.858**	1		
	Sig. (2-tailed)	0.271	0.581	0.174	0			
CM	Pearson Correlation	-0.462	0.17	-0.438	.897**	.947**	1	
	Sig. (2-tailed)	0.13	0.597	0.154	0	0		
EP	Pearson Correlation	0.435	-0.173	0.41	-.868**	-.944**	-.976**	1
	Sig. (2-tailed)	0.158	0.591	0.186	0	0	0	

\*\* Correlation is significant at the 0.01 level (2-tailed).

High humidity reduces solar radiation, most evident when the weather becomes rainy and cloudy, resulting in lower PV output. RH is also highly positively correlated with rainfall ( $r = 0.858, p < 0.01$ ) and cloud cover ( $r = 0.897, p < 0.01$ ), proving a close connection between these climatic variables. Rainfall (R) is strongly and negatively related to energy production ( $r = -0.944, p < 0.01$ ). Increased rainfall leads to heavy cloud cover and reduces solar radiation, resulting in significant decreases in PV electricity production during the rainy season. Rainfall has also been shown to have an extremely positive relationship with cloud cover ( $r = 0.947, p < 0.01$ ). The strongest negative correlation is observed between CM and energy production ( $r = -0.976, p < 0.01$ ), making the latter the dominant climatic condition influencing photovoltaic energy production in this analysis. This means that any increase in cloud cover would block and diffuse solar radiation, thus limiting photovoltaic efficiency. From the correlation analysis, PV energy generation in the Gambia region is positively influenced by both GHI and wind speed, while rainfall, cloud amount, and humidity are significantly and negatively associated with electricity generation. Clouds and rainfall have the greatest negative impact on PV energy generation.

**3.5 Economic analysis results**

The economic assessment examines the feasibility of deploying large-scale photovoltaic (PV) technologies to supply electricity to the government of The Gambia under three scenarios with PV system usage at 50%, 75%, and 100%. This study proposes that the installed PV capacity be 529 MW; the first scenario would indicate that 50% of this capacity is being used (264 MW); the second one would mean that 75% is used (397 MW), while the third one indicates that all of the installed capacity is in use (529 MW). In this paper, the capital cost of the solar power plant is set at 800,000 USD/MW (0.8 USD/W), which accounts for the estimated costs of solar panels, inverters, installation, cabling, and engineering works required for construction. The value is chosen based on the cost range reported in several studies in the international literature on the cost of utility-scale photovoltaic solar energy. The National Renewable Energy Laboratory's annual Technology Baseline Report indicates that utility-scale solar photovoltaic investments range between 0.7 and 1.2 USD/W [58]. Annual operation and maintenance (O&M) costs are estimated at 1.5% of the capital cost, according to the International Renewable Energy Agency [59], amounting to 3.17 million USD per year. O&M costs are estimated as the costs of inspecting, cleaning, maintaining, monitoring, and repairing components to ensure optimal functioning of PV systems over the lifetime of the solar power

plant. Moreover, the project lifetime is set at 25 years, which is equal to the operational life of most contemporary PV plants. Based on a previous study, Sowe et al. [29] evaluated the 1 MW PV plant in Farafenni, The Gambia, and conducted an economic analysis using a 6% discount rate. In this study, the discount rates used in the analysis were set at 6% and 8%. It should be noted that this project includes inverter replacement after 12 years of operation. The cost of replacing the inverters is 15 million USD, as inverters typically last less than PV panels. The salvage value, which accounts for the residual value of system components, is estimated at 10 million USD. Tables 4-6 present an analysis of the economic performance of proposed photovoltaic cell installations at three penetration levels: 50%, 75%, and 100% of the photovoltaic system's contribution to meeting electricity demand. The economic analysis examines the impact of the electricity selling price (ESP), unit deterioration (MD), and discount rate (DR) on the cost of electricity production (LCOE) and the payback period of a photovoltaic solar power project in five selected locations in The Gambia.

It is clear that the discount rate is the primary criterion affecting the cost of electricity production, and that the selling price of electricity is the primary factor affecting the project payback period. The cost of producing photovoltaic solar energy is not affected by the selling price of electricity, as it depends mainly on the project's investment cost, the amount of energy produced, financial conditions, and the system's efficiency during its operating period. For instance, increasing the discount rate from 0% to 8% doubles the LCOE, raising it from about 25-26 USD/MWh to 50-55 USD/MWh, whereas raising the unit degradation rate from 0% to 0.8% raises the LCOE by only US\$2-3/MWh. This clearly demonstrates that financing is far more important in determining the cost of electricity production than the deterioration of units over time. The same phenomenon is evident regarding the project payback period. Higher electricity prices increase project profitability by shortening investment payback periods. In the case of the ESP being equal to 60 USD/MWh, the payback period for the projects varies from 13 to 15 years at a zero discount rate but exceeds 40 years at other rates and reaches even 90 years at the most conservative assumptions (DR = 8% and MD = 0.8%). In the case of increasing the ESP to 100 USD/MWh, the payback period reduces to 6-7 years at a zero-discount rate and is below 11 years even at 8%. This indicates that project revenues are the primary driver of economic feasibility and that favorable electricity prices or other policy tools can be highly beneficial for projects. The payback periods for Banjul are the shortest among all the cases analyzed, demonstrating the best economic performance.

**Table 4.** Economic performance results of proposed PV plants for scenario 1 (PV contribution of 50%)

Location	ESP [USD/MWh]	MD [%]	LCOE [USD/MWh]			Payback Period [Year]		
			DR = 0%	DR = 6%	DR = 8%	DR = 0%	DR = 6%	DR = 8%
Banjul	60	0	25.07	42.36	49.48	13.28	26.29	44.10
		0.5	26.61	44.31	51.54	13.89	29.55	54.81
		0.8	27.56	45.49	52.79	14.30	31.97	64.32
	80	0	25.07	42.36	49.48	8.44	12.32	15.20
		0.5	26.61	44.31	51.54	8.69	12.99	16.30
		0.8	27.56	45.49	52.79	8.84	13.44	17.04
	100	0	25.07	42.36	49.48	6.19	8.05	9.18
		0.5	26.61	44.31	51.54	6.32	8.33	9.57
		0.8	27.56	45.49	52.79	6.40	8.51	9.82
Basse	60	0	25.15	42.50	49.64	13.35	26.59	44.93
		0.5	26.69	44.45	51.70	13.97	29.92	56.09
		0.8	27.65	45.64	52.96	14.38	32.41	66.10
	80	0	25.15	42.50	49.64	8.48	12.41	15.33
		0.5	26.69	44.45	51.70	8.73	13.09	16.45
		0.8	27.65	45.64	52.96	8.89	13.54	17.21
	100	0	25.15	42.50	49.64	6.22	8.09	9.24
		0.5	26.69	44.45	51.70	6.35	8.38	9.63
		0.8	27.65	45.64	52.96	6.43	8.56	9.89
Brikama	60	0	25.48	43.05	50.29	13.66	27.81	48.55
		0.5	27.04	45.03	52.38	14.30	31.48	61.85
		0.8	28.01	46.24	53.65	14.74	34.25	74.24
	80	0	25.48	43.05	50.29	8.65	12.76	15.87
		0.5	27.04	45.03	52.38	8.90	13.48	17.07
		0.8	28.01	46.24	53.65	9.07	13.96	17.89
	100	0	25.48	43.05	50.29	6.33	8.28	9.48
		0.5	27.04	45.03	52.38	6.46	8.57	9.90
		0.8	28.01	46.24	53.65	6.55	8.77	10.17
Farafenni	60	0	25.67	43.37	50.66	13.83	28.56	50.87
		0.5	27.24	45.36	52.77	14.50	32.44	65.66
		0.8	28.22	46.58	54.05	14.94	35.39	79.80
	80	0	25.67	43.37	50.66	8.74	12.96	16.19
		0.5	27.24	45.36	52.77	9.00	13.71	17.44
		0.8	28.22	46.58	54.05	9.17	14.21	18.30
	100	0	25.67	43.37	50.66	6.39	8.39	9.63
		0.5	27.24	45.36	52.77	6.53	8.69	10.05
		0.8	28.22	46.58	54.05	6.62	8.89	10.33
Soma	60	0	25.86	43.69	51.03	14.01	29.32	53.34
		0.5	27.44	45.69	53.15	14.69	33.43	69.84
		0.8	28.42	46.92	54.44	15.15	36.57	86.06
	80	0	25.86	43.69	51.03	8.83	13.17	16.51
		0.5	27.44	45.69	53.15	9.10	13.94	17.82
		0.8	28.42	46.92	54.44	9.27	14.46	18.72
	100	0	25.86	43.69	51.03	6.45	8.49	9.77
		0.5	27.44	45.69	53.15	6.59	8.81	10.21
		0.8	28.42	46.92	54.44	6.68	9.01	10.50

Conversely, SOMA has the highest electricity production cost and the longest payback periods, making it relatively unattractive economically. The differences between the sites considered are small, suggesting that the proposed photovoltaic solar power systems could be economically viable throughout The Gambia, though those in sites with better solar conditions perform slightly better economically. A comparison of the three scenarios for photovoltaic deployment shows that increasing the photovoltaic share from 50% to 75% and then to 100% will have only a slight impact on both the LCOE and the payback periods. For instance, the lowest LCOE value rises only minimally from 25.07 USD/MWh in Scenario 1 to 25.24 USD/MWh in Scenario 3, while the highest LCOE value rises only from 54.44 USD/MWh to 54.85 USD/MWh. Likewise, the shortest payback period increases slightly from 6.19 years to 6.69 years, while the longest payback period increases minimally from 86.06 years to 92.63 years, under the least favorable economic conditions. It appears that increasing PV penetration has a very slight impact on the project's economic characteristics.

The findings show that the proposed photovoltaic systems remain economically viable across a wide range of operating scenarios, especially when the electricity selling price is high and the interest rate is moderate. Furthermore, the study indicates that reducing the cost of capital through concessional financing, low-interest rates, or government investment incentives has a greater effect on economic performance than degradation. This implies that measures that help reduce the cost of capital may be more effective at fast-tracking the widespread adoption of photovoltaic technology than technological advancements that reduce degradation. The slight convergence in performance among the three cases indicates that integrating renewable energy is not overly expensive. The results confirm that widespread deployment of renewable energy, and in this case, widespread deployment of solar photovoltaic energy, can be achieved without compromising the cost economics of the electricity industry. This means that the proposed photovoltaic solar power system would be a reliable approach to achieving the renewable energy goals in The Gambia.

**Table 5.** Economic performance results of proposed PV plants for scenario 2 (PV contribution of 75%)

Location	ESP [USD/MWh]	MD [%]	LCOE [USD/MWh]			Payback Period [Year]		
			DR = 0%	DR = 6%	DR = 8%	DR = 0%	DR = 6%	DR = 8%
Banjul	60	0	25.15	42.55	49.67	13.28	26.51	44.77
		0.5	26.70	44.50	51.73	13.89	29.85	55.93
		0.8	27.65	45.69	52.98	14.30	32.34	65.94
	80	0	25.15	42.55	49.67	8.44	12.35	15.25
		0.5	26.70	44.50	51.73	8.68	13.03	16.36
		0.8	27.65	45.69	52.98	8.84	13.49	17.12
	100	0	25.15	42.55	49.67	6.18	8.05	9.19
		0.5	26.70	44.50	51.73	6.31	8.34	9.58
		0.8	27.65	45.69	52.98	6.39	8.52	9.84
Basse	60	0	25.24	42.68	49.83	13.35	26.80	45.62
		0.5	26.78	44.64	51.90	13.97	30.23	57.27
		0.8	27.74	45.84	53.16	14.39	32.78	67.81
	80	0	25.24	42.68	49.83	8.48	12.44	15.38
		0.5	26.78	44.64	51.90	8.72	13.13	16.51
		0.8	27.74	45.84	53.16	8.88	13.59	17.29
	100	0	25.24	42.68	49.83	6.21	8.10	9.25
		0.5	26.78	44.64	51.90	6.34	8.38	9.65
		0.8	27.74	45.84	53.16	6.42	8.57	9.91
Brikama	60	0	25.56	43.24	50.48	13.65	28.05	49.37
		0.5	27.13	45.23	52.57	14.31	31.82	63.30
		0.8	28.10	46.44	53.85	14.74	34.67	76.43
	80	0	25.56	43.24	50.48	8.64	12.79	15.93
		0.5	27.13	45.23	52.57	8.89	13.52	17.14
		0.8	28.10	46.44	53.85	9.06	14.01	17.98
	100	0	25.56	43.24	50.48	6.32	8.28	9.49
		0.5	27.13	45.23	52.57	6.45	8.58	9.91
		0.8	28.10	46.44	53.85	6.54	8.78	10.19
Farafenni	60	0	25.75	43.56	50.85	13.83	28.82	51.77
		0.5	27.33	45.56	52.96	14.50	32.81	67.31
		0.8	28.31	46.78	54.25	14.95	35.84	82.36
	80	0	25.75	43.56	50.85	8.73	13.00	16.25
		0.5	27.33	45.56	52.96	8.99	13.75	17.52
		0.8	28.31	46.78	54.25	9.16	14.26	18.39
	100	0	25.75	43.56	50.85	6.38	8.39	9.64
		0.5	27.33	45.56	52.96	6.52	8.70	10.07
		0.8	28.31	46.78	54.25	6.61	8.90	10.35
Soma	60	0	25.94	43.88	51.22	14.01	29.59	54.34
		0.5	27.53	45.89	53.35	14.70	33.82	71.72
		0.8	28.52	47.12	54.64	15.16	37.06	89.06
	80	0	25.94	43.88	51.22	8.83	13.21	16.58
		0.5	27.53	45.89	53.35	9.09	13.99	17.90
		0.8	28.52	47.12	54.64	9.27	14.51	18.82
	100	0	25.94	43.88	51.22	6.44	8.50	9.78
		0.5	27.53	45.89	53.35	6.58	8.82	10.23
		0.8	28.52	47.12	54.64	6.67	9.02	10.52

**4. Discussions**

The results demonstrated that The Gambia has enormous solar energy resources that can be used to generate electricity using PV. The GHI in The Gambia ranged from 5.776 to 5.886 kWh/m<sup>2</sup>/day across the five sites selected for the study, indicating that the country’s solar resources are uniformly high. This is consistent with results from other West African countries, such as Senegal, Ghana, and Mali, where the global solar irradiance index exceeds 5.5 kWh/m<sup>2</sup>/day and is therefore suitable for large-scale photovoltaic applications. Furthermore, seasonal climate variability was identified as the dominant factor affecting the solar system’s performance. Based on the results, electricity generation was highest during the dry season due to lower cloud cover, humidity, and rainfall, while the rainy season led to a decrease in electricity generation due to increased atmospheric absorption of solar radiation. Similar patterns of seasonality have been observed in the monsoon region of West Africa, where cloud formation and rainfall have reduced the availability of solar radiation [60, 61].

According to the correlation analysis, GHI and wind speed positively influenced electricity generation from photovoltaic systems, whereas rainfall, cloud cover, and relative humidity negatively affected it. All the climatic parameters analyzed in this study indicate that cloud cover exhibits the strongest negative correlation with electricity production ( $r = -0.976$ ), followed by rainfall ( $r = -0.944$ ). These results indicate that atmospheric attenuation from clouds and rain is the main reason for the decrease in solar energy production during the rainy season. This conclusion has also been highlighted by Danso et al. [61]. Besides, air temperature correlated poorly and negatively with energy generation in PV systems due to high module temperatures reducing photovoltaic efficiency. While areas with high solar intensity usually record high temperatures, the latter leads to increased resistance in semiconductors and reduced efficiency. Such effects on PV efficiency have been reported in other studies on PV systems in tropical and subtropical regions [62].

**Table 6.** Economic performance results of proposed PV plants for scenario 3 (PV contribution of 100%)

Location	ESP [USD/MWh]	MD [%]	LCOE [USD/MWh]			Payback Period [Year]		
			DR = 0%	DR = 6%	DR = 8%	DR = 0%	DR = 6%	DR = 8%
Banjul	60	0	25.24	42.72	49.85	13.32	26.79	45.61
		0.5	26.79	44.68	51.92	13.94	30.22	57.30
		0.8	27.75	45.88	53.18	14.35	32.78	67.89
	80	0	25.24	42.72	49.85	8.45	12.42	15.35
		0.5	26.79	44.68	51.92	8.70	13.11	16.49
		0.8	27.75	45.88	53.18	8.86	13.57	17.26
	100	0	25.24	42.72	49.85	6.19	8.08	9.23
		0.5	26.79	44.68	51.92	6.32	8.37	9.63
		0.8	27.75	45.88	53.18	6.41	8.55	9.89
Basse	60	0	25.32	42.86	50.01	13.39	27.09	46.50
		0.5	26.88	44.83	52.09	14.02	30.61	58.71
		0.8	27.84	46.03	53.35	14.44	33.24	69.88
	80	0	25.32	42.86	50.01	8.49	12.50	15.49
		0.5	26.88	44.83	52.09	8.74	13.20	16.64
		0.8	27.84	46.03	53.35	8.90	13.67	17.43
	100	0	25.32	42.86	50.01	6.22	8.13	9.29
		0.5	26.88	44.83	52.09	6.35	8.42	9.69
		0.8	27.84	46.03	53.35	6.44	8.61	9.96
Brikama	60	0	25.65	43.42	50.66	13.70	28.37	50.39
		0.5	27.23	45.41	52.77	14.36	32.25	65.05
		0.8	28.20	46.63	54.05	14.80	35.18	79.05
	80	0	25.65	43.42	50.66	8.66	12.86	16.04
		0.5	27.23	45.41	52.77	8.92	13.60	17.28
		0.8	28.20	46.63	54.05	9.08	14.10	18.13
	100	0	25.65	43.42	50.66	6.33	8.31	9.54
		0.5	27.23	45.41	52.77	6.47	8.62	9.96
		0.8	28.20	46.63	54.05	6.55	8.82	10.24
Farafenni	60	0	25.85	43.74	51.04	13.88	29.15	52.90
		0.5	27.43	45.75	53.16	14.55	33.26	69.29
		0.8	28.41	46.97	54.45	15.01	36.39	85.41
	80	0	25.85	43.74	51.04	8.75	13.07	16.37
		0.5	27.43	45.75	53.16	9.02	13.84	17.66
		0.8	28.41	46.97	54.45	9.19	14.35	18.55
	100	0	25.85	43.74	51.04	6.39	8.42	9.68
		0.5	27.43	45.75	53.16	6.53	8.74	10.12
		0.8	28.41	46.97	54.45	6.62	8.94	10.41
Soma	60	0	26.03	44.06	51.41	14.06	29.95	55.58
		0.5	27.63	46.08	53.55	14.75	34.30	73.97
		0.8	28.62	47.32	54.85	15.21	37.64	92.63
	80	0	26.03	44.06	51.41	8.85	13.28	16.70
		0.5	27.63	46.08	53.55	9.12	14.07	18.05
		0.8	28.62	47.32	54.85	9.29	14.61	18.98
	100	0	26.03	44.06	51.41	6.45	8.53	9.83
		0.5	27.63	46.08	53.55	6.60	8.85	10.28
		0.8	28.62	47.32	54.85	6.69	9.06	10.57

Additionally, wind speed showed a moderate positive correlation with PV production, as higher wind speeds facilitate the natural cooling of solar panels. The coastal areas of Banjul and Brikama also experienced slight positive effects from increased wind speeds and reduced heat loss. In previous research on PV efficiency in hot climates, the effect of wind speed on solar panel cooling was also highlighted [62]. Moreover, the energy production analysis revealed the ability to generate significant electricity across all scenarios considered. Scenario 3, featuring a 100% PV penetration rate, produced the most electricity annually, exceeding 900,000 kWh in several locations. Annual electricity production fluctuated with seasonal variations; thus, the highest output was observed during the dry period due to peak solar irradiance. These results are consistent with the literature, suggesting that electricity production during the dry season in West Africa is considerably higher than during the rainy season due to fewer clouds and lower water vapor content [60]. Annual capacity factor values ranged from approximately 19% to 20%,

indicating good PV system performance in a tropical environment. This result is consistent with capacity factor values recorded for large-scale PV systems in areas of Africa with high solar irradiation. The reason is that the capacity factor is affected mostly by climatic conditions and solar resource availability. Thus, the capacity factor remains stable across various scenarios, as the number of installed systems does not significantly affect it. The loss assessment indicates that total losses were between 21 and 23 percent. Losses due to temperature and irradiance are dominant among all other loss types. The angle of incidence was kept relatively low because the systems were installed by optimizing the slope and azimuth angles. Regions with high ambient temperatures and humidity experienced greater operational losses. This is due to thermal losses and atmospheric attenuation of incoming solar radiation. Performance losses in the studied regions were similar to those reported in other research conducted under hot and humid conditions. Based on the results of the economic analysis, it is possible to state that the realization of large-scale solar PV is highly feasible in The Gambia.

According to the estimations performed, the LCOE value is in the range of 50-55 USD/MWh under the most realistic financing assumptions (DR = 8%), which is in line with recent research on utility-scale solar photovoltaic projects in West Africa. Similar values have been obtained for neighboring countries where utility-scale solar photovoltaic power has gained increasing competitive advantages due to lower energy production costs. For instance, the International Renewable Energy Agency (IRENA) [59] reported that the global weighted-average LCOE for large-scale solar photovoltaic projects had fallen to around 44 USD/MWh, with the majority of African projects having an LCOE between 40 USD/MWh and 70 USD/MWh. Ogunjuyigbe et al. [63] found that the LCOE of large-scale photovoltaic solar power plants installed in Nigeria ranged from 47 to 50 USD/MWh. Okeke et al. [64] found an LCOE of 40 USD/MWh for utility-scale solar photovoltaic in Nigeria. Asare-Addo [65] found that the LCOE ranged from 40 USD/MWh to 150 USD/MWh. Besides, the payback period is less than six years, regardless of the scenario or region. These economic results align with earlier studies on renewable energy in Africa, which found that declining PV technology costs and high levels of solar radiation increase the economic viability of solar power plants [66,67]. Generally, this outstanding performance was enhanced by the selection of n-type tunnel-oxidized contact photovoltaic (TOPCon) modules. The TOPCon modules have a lower temperature coefficient ( $-0.29$  to  $-0.32\%/^{\circ}\text{C}$ ) than the traditional polycrystalline and PERC technologies ( $-0.35$  to  $-0.45\%/^{\circ}\text{C}$ ), which makes them more efficient at generating heat during operation in tropical climates [68,69]. Apart from that, TOPCon photovoltaic modules have higher efficiency, a lower degradation rate, and a longer lifetime energy output compared with traditional silicon photovoltaic modules, thereby increasing the power station's efficiency and lowering the LCOE [70,71]. Thus, the choice of TOPCon modules is optimal for The Gambia's hot climate.

## 5. Limitations and future study

In this study, several limitations must be taken into consideration. The resource estimation was based on NASA Power reanalysis data, which is highly consistent in its long-term spatial coverage, although it may miss some local climate variations and short-term fluctuations in solar radiation. Ground-based observations using solar radiation measuring devices can also provide more accurate data regarding resource assessment and verification of modeling results. Therefore, future research needs to integrate long-term ground-based, remote sensing, and reanalysis data. Additionally, a deterministic mathematical model has been adopted, and no probabilistic uncertainty analysis, such as Monte Carlo simulations, has been conducted to quantify uncertainties in solar irradiation, energy production, levelized cost of energy, or payback period. Nevertheless, the reliability of the results has been assessed by conducting a sensitivity analysis of key economic variables, including the discount rate, the selling price of electricity, and the degradation rate of the modules. For future research, a probabilistic analysis should be included. In addition, the study has examined bifacial TOPCon photovoltaic panels coupled to utility-scale string inverters without comparing their performance with that of other commercially available photovoltaic modules, such as PERC or HJT modules. Further research needs to include probabilistic uncertainty analysis and techno-economic analysis of alternative photovoltaic technologies and inverters, as well as future scenarios (2030 and 2040) that incorporate future technology costs and energy storage systems.

## 6. Conclusions

The present study aimed to analyze the technical and economic feasibility of photovoltaic power generation in The Gambia based on climate analysis, photovoltaic power generation performance, and economic evaluation. The results indicated that Gambia has sufficient solar energy potential, with annual global horizontal irradiance ranging between 5,776 and 5,886 kWh/m<sup>2</sup>/day across all selected study sites. Additionally, the performance evaluation results indicated that solar electricity production depends on the seasons. Besides, during the dry season, energy production was higher due to higher solar radiation and lower cloud cover, whereas rainfall and cloud cover were the most important factors affecting photovoltaic energy production in the rainy season. Furthermore, the proposed solar power systems showed an annual power factor of 19-20%. The economic study demonstrated the feasibility of large-scale photovoltaic power plant development. Under different scenarios, the LCOE ranged from 50 to 55 USD/MWh. The results show that large-scale photovoltaic power plants can provide competitive electricity generation while reducing dependence on foreign fossil fuels. In terms of policy, the research findings justify increased government investment in large-scale solar power plants in The Gambia. To encourage the development of more solar energy in the country, the government should focus on implementing policies such as promoting renewable energy, developing grid infrastructure, securing climate finance, and integrating energy storage technology into its energy transition plan.

### Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

### Data availability statement

The manuscript contains all the data. However, additional data will be provided by the corresponding author upon reasonable request.

### Conflict of interest

The authors declare no potential conflict of interest.

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