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Effects of photovoltaic power plants connected to the grid from 2016 to 2022 in Senegal on carbon dioxide emissions

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Abstract

The use of fossil fuels for energy production has caused global warming, the main environmental concern of our society. Today, renewable energy sources offer a solution to this problem, and the government of Senegal is working to promote the renewable energy sector in order to combat global warming and produce reliable, affordable, and sustainable energy. The current work seeks to study the contribution of photovoltaic power plants to the reduction of greenhouse gas emissions, particularly carbon dioxide. Photovoltaic system operation, depending on atmospheric parameters, utilizes the RETScreen software to collect weather data such as ambient temperature, irradiation, and wind velocity for each location. Mathematical equations modeling the temperature, efficiency, and power of a photovoltaic module are used in this work to determine the influence of atmospheric conditions on solar power plants. The results showed that weather parameters have a significant influence on energy production. The results also demonstrated Senegal's contribution to the reduction of greenhouse gases with 194.228 MegaWatts (MW) of solar photovoltaic plants. This contribution consisted of injecting 364.746 GigaWatt-hours (GWh) of clean energy per year, i.e., 7294.920 GWh over 20 years, and in reducing 314,411.1 tons of carbon dioxide per year, i.e., 62,288,222 tons over 20 years.

Keywords: CO_2 reduction, Greenhouse gas, Global warming, Renewables energies, Photovoltaic power plants, Senegal.

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Contribution of this paper to the literature
This work is the first scientific study carried out in Senegal to determine the amount of carbon dioxide that photovoltaics power plants will reduce in 20 years' time. This work determines the influence of atmospheric conditions on installed photovoltaic power plants.

1. Introduction

In 2017, out of 357 million people living in the Economic Community of West African States (ECOWAS) region, 171 million were without electricity [1]. A large part of the energy produced in this region comes from fossil fuels. The combustion of fossil fuels emits greenhouse gases, thus increasing global warming. Therefore, the energy transition (from fossil energies to renewable energies) is still topical issue. In 2015, an agreement was signed in Paris (at COP21). Such an agreement aims at reducing the rate of carbon emissions worldwide to such an extent that the global average temperature should not exceed 2°C (and even 1.5°C) above preindustrial levels for this century [2-6]. This situation provides a favorable ground for the use of renewable energies which is becoming increasingly one of the major focuses of the world's population. The most widespread renewable energies are biomass, hydroelectricity, wind and solar energies. In Africa, many actors such as states and organizations impact the energy transition [7]. In this logic, ECOWAS countries will invest about €1.773 million in photovoltaic (PV) solar energy before 2030 [3, 8]. It is important to note that in West Africa, the daily average solar radiation is 5-6k$W\ h/m^2/day$ [3]. In addition, the source of this energy is available everywhere in Sub-Saharan Africa [9]. In recent decades, it has been noted that solar PV has undergone very significant development [10]. Senegal, for example, has been developing reform policies in the energy sector since 2010, particularly in the area of green (renewable) energy [11]. Senegal is a West African country which is located at latitude 14°43'29 North, longitude 17°28'24 West with a total area of about 196,700 km2, and a population of over 15 million people. The Institute of Meteorological Physics (IMP) is the first institute of solar energy research. It was established at the University of Cheikh Anta Diop of Dakar in 1962 and was renamed Centre for Studies and Research on Renewable Energies (CSRRE) in 1975 [12]. In Senegal, 60% of the population are rural residents, and only 40% of people living in rural areas have access to electricity. The connection of solar photovoltaic plants will enable the country to reduce its electricity imports still further by up to 15% [1]. Between 2016 and 2022, the Senegalese government installed eight photovoltaic solar power plants connected to the grid. These include Bokhol, Malicounda, Tène Merina, Sakal, Diass, Santhiou Mekhe and Kahone. These green power generation systems will help to reduce greenhouse gas emissions knowing that every kWh produced corresponds to a reduction in the use of fossil fuels. However, there is no scientific research to determine the quantity of carbon dioxide that can be saved by these solar power plants.

The aim of this work is to study the effect of these PV power plants on carbon dioxide emissions, one of the greenhouse gases, considering meteorological parameters such as temperature, solar irradiation and wind speed. To achieve this aim, the current paper is organized as follows: the PV solar plant sites and the methodology will be described in Section 2, starting with a presentation of Senegal's PV solar potential. The results obtained from the methodology will be presented and discussed in Section 3. The last section of this paper is the conclusion.

2. Presentation of the Sites and Methodology

In this section, we will present the map of Senegal's solar potential and the sites where photovoltaic power plants are installed, and develop the methodology used.

2.1. Photovoltaic Solar Potential in Senegal

Figure 1 shows a map of Senegal and the corresponding solar potential. It can be seen that certain areas of Saint-Louis, Louga and Fatick regions and the entire Dakar region have the highest solar potential in Senegal, at over 4.8 kWh/kWp. In fact, the eight power plants studied in this research work are located in above-mentioned regions. The least unfavorable areas are in the regions of Tambacounda, Kédougou, Kolda and Ziguinchor.

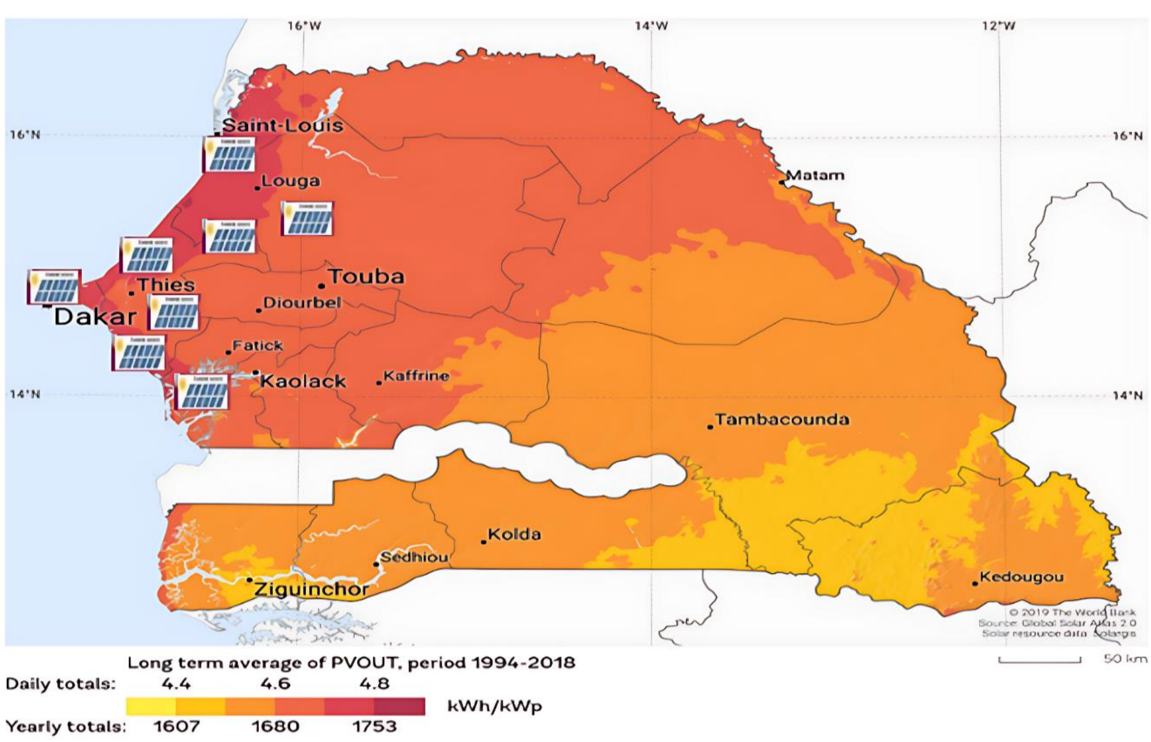

Figure 1. Photovoltaic power potential in Senegal.

Source: Abdoulaye, et al. [13].

2.2. Locations for PV Power Plants

Bokhol, in the Saint-Louis region, is the first solar photovoltaic power plant in Senegal or even in West Africa. Saint-Louis is located at latitude 16.05° N and longitude -16.45° E. Our second solar power plant is located in Kahone. Kahone was a town in the Fatick region before being classified in the Kaolack region of Senegal. The geographical coordinates are: latitude 14°13 N and longitude -16°07 E. The third PV power plant in this study is located in Sakal.

Sakal is located 27 km from Louga, with geographical coordinates of 15°62 N latitude and -16°22 E longitude. The solar power plant is located 3 km from Sakal. Finally, the Diass, Malicounda, Ten Merina and Santhiou Methe power plants are located in the Thies region, where the geographical coordinates are 14°38'21 N and 17°5'16 W.

2.3. Methodology

The efficiency of a PV module in the laboratory is low. It is 0.1575 for the solar modules installed in the power plants studied in this work. When the PV module is in operation, its efficiency depends on the temperature and irradiation of the installation site. Equation 1 gives the efficiency of a photovoltaic panel [14].

$$r_{PV} = r_{STC}\left(1 - a\left(T_{PV} - T_{ref}\right) + b.\ln\left(\frac{G_m}{1000}\right)\right) \quad (1)$$

Where:

- r_{STC} is the module efficiency under standard conditions, i.e T_{PV}=T_{ref} = 25°C, G_m = 1000 W/m² and air density =1.5;
- T_{ref} is the reference temperature;
- G_m is the irradiation of the area where the module is installed;
- T_{PV} is the module temperature, a is the temperature coefficient and is equal to -0.0045 and b, the solar irradiation coefficient, is equal to 0.11.

The temperature of the PV noted T_{PV} varies according to weather conditions. In this study, we will use the mathematical Equation 2 modelling temperature as a function of ambient temperature, irradiation and wind speed.

$$T_{PV} = T_{am} + \frac{G_m}{(C_1 + C_2.v_s)} \quad (2)$$

Where:

- T_{am} is the ambient temperature;
- v_s is the wind speed;
- C_1 and C_2 are empirical coefficients whose values are respectively equal to 32.12 W/(°Cm²) et 4.51 Ws/(°Cm³).

The output power of a PV solar module noted P_{S_PV} is modelled by Equation 3, which shows its dependence on variations in weather conditions.

$$P_{S\_PV} = \frac{P_{PV\_STC}.G_m.r_{PV}}{1000.r_{STC}} \quad (3)$$

Where: P_{PV_STC} is the peak power of the module.

The PV temperature is calculated from Equation 2, the result of which will be used to find the PV efficiency given by Equation 1.

The objective is to determine the quantity of carbon dioxide (CO_2), one of the greenhouse gases, that can be reduced by the four proposed PV power plants. To calculate the quantity reduced by each PV plant, Equation 4 is proposed [15].

$$Q_{CO_2}(redu) = F_{em}.E_{grid} = 0.862 * E_{grid} \quad (4)$$

Where:

E_{grid} is the energy generated by the PV module that is expressed in MWh, F_{em} is the greenhouse gas emission factor, whose value is equal to 0.862 kgCO2/kWh or 0.862 tCO2/MWh for Senegal. This value is given by the RETScreen software. E_{grid} is calculated by Equation 5:

$$E_{grid} = P_{S\_PV}.t(h) \quad (5)$$

Where t(h) is the PV operating time in hours, i.e. 360 hours per month or 12 hours per day in Senegal.

3. Results and Discussion

In this section, the meteorological data obtained using the RETScreen software are used to determine the temperatures, efficiencies and output powers of the PV modules. The ambient temperatures, wind speeds and module temperatures are shown in Figure 2, 3 and 4. These characteristics are not represented for the Malicounda, Ten Merina and Santhiou Mekhe sites, as these sites are in the same geographical area as Diass.

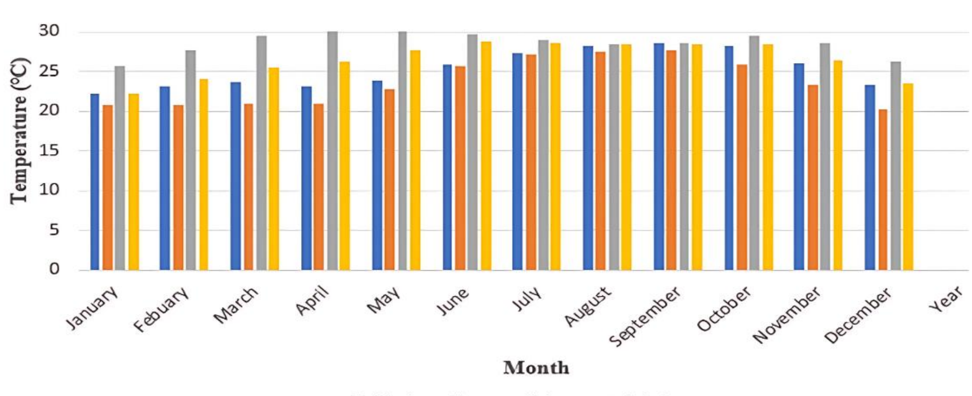

Figure 2. Variation of the ambient temperature at PV power plant sites over the year.

Figure 2 shows the ambient temperatures at the sites of the four power stations. The figure shows that the town of Kahone has the highest temperature every month, followed by the town of Sakal. Diass has the lowest temperature.

Figure 3 shows the different wind speeds. It can be seen that, contrary to the temperature, Kahone and Sakal have respectively the lowest and highest wind speeds. After Sakal, Diass comes second, followed by Bokhol.

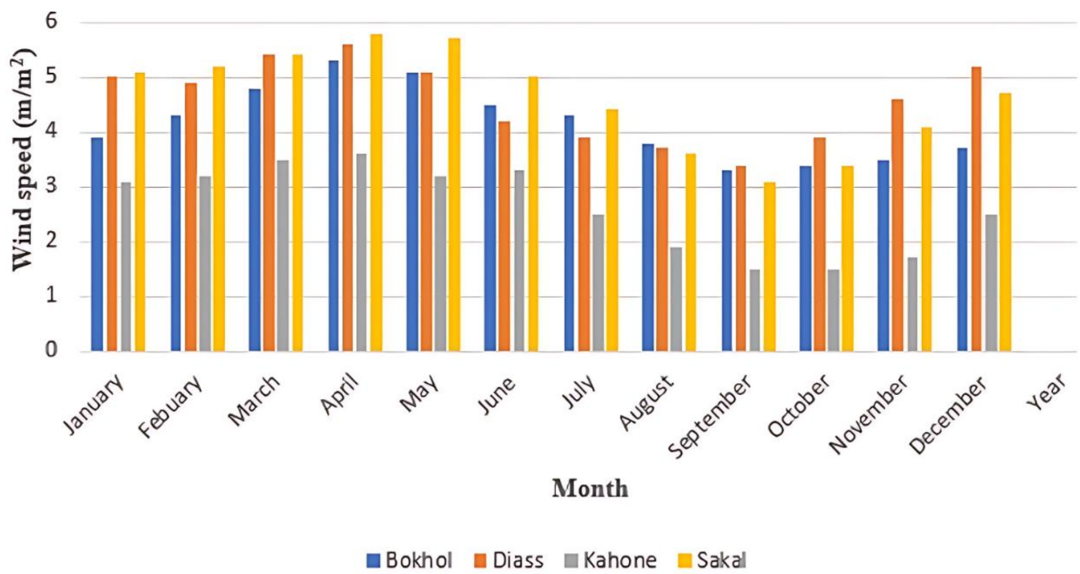

Figure 3. Variation of wind speed at PV power plant sites over the year.

Using the results shown in Figure 2 & 3, the PV module temperatures for four PV power plants are determined and illustrated in Figure 4. This shows that the monthly temperatures of the modules are higher than those of the environment in which they are installed. At Kohone, the temperature can exceed 40°C. This may be due to the low wind speed. Diass had the lowest module temperatures. These results confirm the dependence of PV panel temperature on wind speed and ambient temperature.

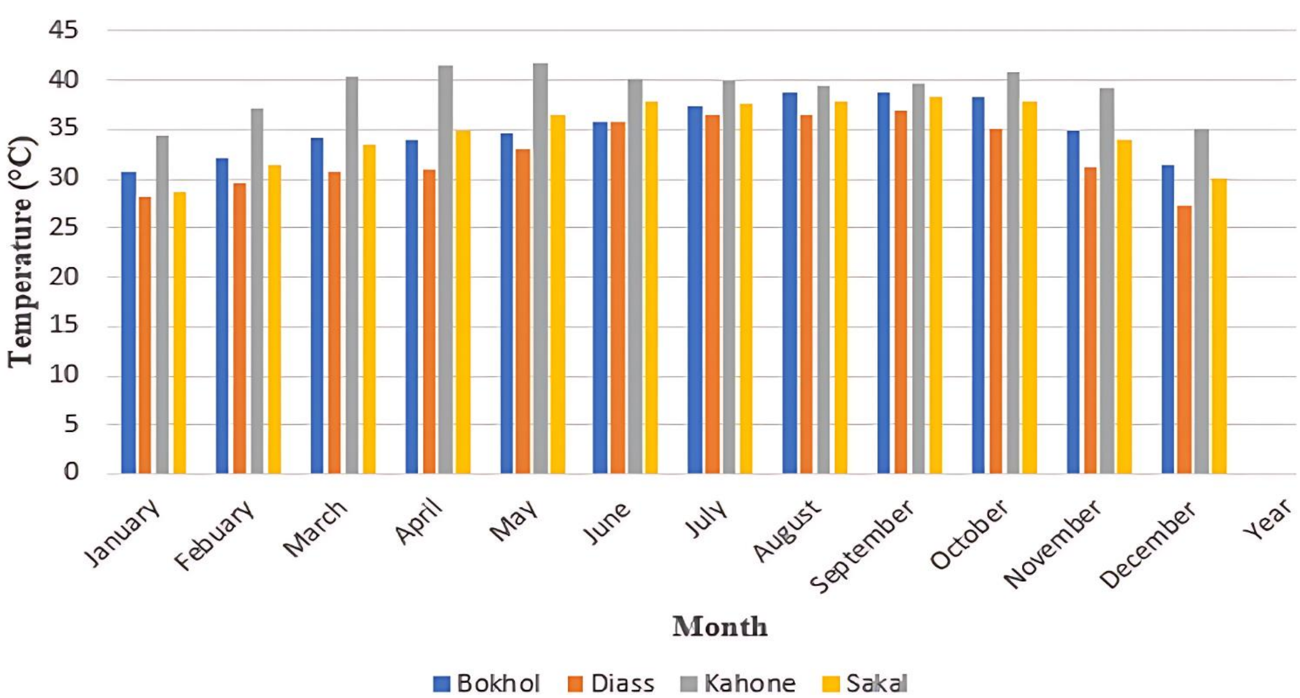

Figure 4. Variation of the PV module temperature over the year.

Table 1 represents the PV module efficiencies of the four PV solar power plants. This table shows that the modules installed at Bokhol have a higher efficiency than the other sites, except in June when Sakal has a slightly higher efficiency. This can be explained by the fact that the wind speed in June is higher at Sakal than Bokhol.

Table 1. The PV module efficiencies of the four PV solar power plants.

January	**0.1462**	**0.1441**	**0.1439**	**0.1418**
February	0.1489	0.1481	0.1466	0.1462
March	0.1539	0.1510	0.1502	0.1499
April	0.1551	0.1522	0.1516	0.1525
May	0.1551	0.1530	0.1527	0.1538
June	0.1541	0.1536	0.1529	0.1543
July	0.1551	0.1524	0.1527	0.1531
August	0.1559	0.1516	0.1518	0.1530
September	0.1547	0.1519	0.1516	0.1531
October	0.1539	0.1512	0.1507	0.1524
November	0.1493	0.1466	0.1469	0.1472
December	0.1458	0.1423	0.1423	0.1430
Sites	Bokhol	Diass	Kahone	Sakal

Table 2 shows the power output, energy injected into the grid and quantities of CO_2 reduced per year. These 8 plants will enable 364.746 GWh to be fed into the grid every year, i.e. 7294.920 GWh over 20 years. After all, a solar power plant can operate for at least 20 years. In terms of contribution to the reduction of carbon dioxide emissions, 314411.1 tons will be reduced per year, i.e. 62288222 tons over 20 years.

Table 2. Energy injected (MWh) to grid & quantity of CO2 reduced (tons) in year.

Solar power plant	Power (W)	Energy injected (MWh) in year	Quantity of CO_2 reduced (Tons) in year
Bokhol	20	32965.5	28416.3
Diass	17	34914.6	30096.4
Kahone 1	21.228	31059.5	26773.3
Kahone 2	35	70371.1	60659.8
Sakal	20	29077.5	25064.8
Ten Merina	29.5	60587.1	52226.1
Santhiou Mekhe	29.5	60587.1	52226.1
Malicounda	22	45183.6	38948.3
Total	194.228	364746	314411.1

4. Conclusion

The effect of photovoltaic power plants installed in Senegal on carbon dioxide emissions has been studied in this work. Instead of taking the value of installed power directly to calculate the quantity of CO_2 reduced, mathematical equations are used to find a more accurate quantity. This approach allowed us to determine the quantity of CO_2 reduced per year and to see the influence of meteorological parameters on the energy produced by PV power plants.

In the future, the use of experimental values will enable a good estimate of reduced CO_2 to be made.

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