

Research Article

Study of the Seasonal Effect of Atmospheric Parameters on Solar Photovoltaic Production in Burkina Faso, West Africa

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Abstract

The work presented is an analysis of solar photovoltaic production, the objective of which is to study the effect of seasonal atmospheric parameters on the production of solar photovoltaic power plants in Burkina Faso. It is a study based on in situ measurements and observation data from the MODIS sensor aboard the Terra satellite. Thus, an analysis of aerosol variability at the national scale shows that aerosol levels peak during the winter months of February, the spring months of March, April, and May, and the summer month of June. This distribution of aerosols is consistent with the dynamics of the Harmattan wind and convective systems, which explain the nature of aerosols dominated by coarse particles associated with desert dust. Furthermore, this seasonality of aerosols is confirmed by the annual cycles of AOD and Angstrom coefficient observed at the study sites where the power plants are located. In addition, a combined qualitative analysis of the AOD cycle and available solar potential shows the direct effect of aerosols on the radiation required for solar photovoltaic conversion. This effect of aerosols on solar power plant output is corroborated by a negative correlation that demonstrates their significant ability to influence the efficiency of solar power plant output. Furthermore, the study of the seasonal effect of climatic parameters indicates, through annual cycles and correlation coefficients, the negative impact of temperature and relative humidity on the output of solar photovoltaic systems. This is contrary to the effect of sunlight, although it depends on the weather, location, and environmental factors. The same applies to wind speed, which is favorable to the production cycle of power plants, although it is the main vector for the emission of mineral dust that settles on the surface of the modules. In short, atmospheric parameters generally have a negative impact on photovoltaic power plant production in a Sahelian-type climate strongly influenced by desert dust.

Keywords

Aerosol, Climate Parameters, Solar Photovoltaic Production, MODIS, Burkina Faso

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1. Introduction

Conventional fossil fuels such as oil, coal, and natural gas are the main sources of energy that are widely used [1]. However, the availability of these sources is limited, and their exploitation, from extraction to processing, poses an existential threat to the environment and the entire planet [2, 3]. In fact, approximately 66% of global emissions of carbon dioxide and other greenhouse gases come from fossil fuels [1, 4]. In addition, the combustion of fossil fuels and biomass accounts for approximately 85% of air pollution from particulate matter and almost all sulfur and nitrogen oxide emissions in developed countries [3]. According to the IPCC report in 2013, these emissions are causing intense warming, leading to heat waves and influencing the hydrological cycle, which explains the precipitation anomalies and extreme events observed in the form of flooding in several regions of the world [5]. Every year, 4 to 7 million people die prematurely and hundreds of millions more suffer from diseases caused by air pollution, which is responsible for enormous suffering [6]. Solar energy, in particular, is the most suitable form of renewable energy, as it is easily accessible, environmentally friendly, and non-polluting [6, 7]. To this end, the African continent, particularly the northern and southern parts, has enormous potential in terms of available solar energy that is suitable for solar photovoltaic conversion [8, 9]. This is corroborated by several studies that have shown the importance of the solar potential available in northern regions, particularly the Sahel, with average monthly irradiation values reaching up to 6 kWh/m²day [10-12]. According to the International Energy Agency, photovoltaic (PV) systems could provide 11% of global renewable energy, which is equivalent to a significant reduction of 2.3 gigatons of carbon dioxide (CO₂) emissions per year [1]. In Burkina Faso, electricity is mainly generated by thermal and hydroelectric power plants. There are few solar power plants, yet energy is a fundamental issue. As a result, photovoltaic solar power plants have been built in recent years to take advantage of the country's abundant solar potential [11]. Aware that energy is at the heart of all economic and social development processes, Burkina Faso has committed, through its Ministry of Energy, to devote considerable effort and resources to making energy available and accessible to all by diversifying energy sources through the use of renewable energies, particularly solar photovoltaic energy. However, solar energy production is intermittent, and several climatic and environmental factors impact this energy production and the efficiency of photovoltaic modules. Indeed, the efficiency of a solar photovoltaic system depends heavily on solar radiation, which is unpredictable [13] and influenced differently by weather conditions, seasonal variations, location, time of day, and the position and height of the sun [14, 15]. Temperature is also a parameter that negatively impacts the efficiency of photovoltaic cells, as it is inversely proportional to voltage [1]. To this end, at an operating temperature of 56 °C under an irradiance of 1000 W/m², the efficiency of the cell decreases by 3.13% [16], and a 5% decrease is recorded when the module temperature increases from

43 °C to 47 °C [17]. In addition, the absorption and heat dissipation properties of the encapsulation material greatly affect the performance of the photovoltaic system [18]. In addition, particles suspended in the atmosphere, such as aerosols, pollutants, and water vapor, absorb or scatter incident solar radiation, thereby reducing the amount of radiation transmitted for photovoltaic solar conversion [19]. This is also the case with the accumulation of dust that forms on the surface of the modules and then forms a layer that attenuates part of the solar radiation incident on the surface of the solar panel [18, 20]. However, these dust deposits are due to environmental factors such as wind speed, humidity, convective systems, emission sources, particle type, and the nature of the surface of PV solar modules [1]. Humidity significantly influences the adhesive force between particles and the surface of PV modules and can even lead to the formation of a paste-like layer in the form of mud [21, 22]. In addition, when relative humidity is very high, fine water droplets can form on the surface of solar panels and contribute to the diffusion of solar radiation. Thus, prolonged exposure to a humid environment corrodes photovoltaic modules through moisture intrusion into the photovoltaic cells [23, 24]. Furthermore, the presence of moisture in the enclosure increases the conductivity of the material and leakage currents [25]. Added to this is the risk of delamination and discoloration of the photovoltaic module when the rate of corrosion caused by water condensation at the interface between the encapsulant and the solar cell materials increases [24, 25]. The impact of wind on solar photovoltaic conversion depends on its direction and speed, as it allows heat to be removed from the solar modules by convection and influences dust deposits depending on the surface structure of the PV modules [26, 27]. Given the complexity involved in forecasting the electrical energy produced by solar photovoltaic systems, which is highly dependent on environmental factors, we are focusing our work on analyzing solar photovoltaic production with the aim of studying the effect of seasonal atmospheric parameters on the production of solar photovoltaic power plants in Burkina Faso, which has a Sahelian climate. Specifically, we will show the seasonal variability of aerosols strongly influenced by desert dust and then highlight their influence on the output of photovoltaic power plants. In addition, based on a study of the correlation between climatic parameters and the solar energy produced, we will describe the seasonal impact of climatic parameters on the solar conversion of these power plants.

2. Materials and Methods

2.1. Study Area and Sites

Burkina Faso is a landlocked country in West Africa with a total area of approximately 274,200 km² [28]. It is bordered by Mali to the west and north, Niger to the northeast and east, Benin to the southeast, and Togo, Ghana, and Côte d'Ivoire to

the south [29]. Burkina Faso's climate is subdivided into three climatic zones: the arid Sahel in the north, the semi-arid Sudano-Sahelian zone in the center, and the subhumid Sudanese climate zone in the south [30, 31]. All these climatic zones experience two main seasons: a longer dry season covering the period from November to May and a wet season from June to October [32-34]. These two seasons are directly linked to the monsoon and harmattan winds that characterize atmospheric circulation in West Africa. In recent years, Burkina Faso has opted to diversify its energy sources by turning to renewable energies, particularly solar photovoltaic energy. To this end, several solar photovoltaic power plants have been built, including the Zagtouli solar photovoltaic power plant (12.31°N, -1.64°E) and the Nagreongo solar photovoltaic power plant (12.45°N, -1.25°E). Zagtouli is a town located in the 8th district of Ouagadougou (12.20°N; -1.40°E), the capital of Burkina Faso in the central region. It is located in the southwest of the capital, about 20 kilometers from the city center. Nagreongo, on the other hand, is a rural commune located in the central plateau region, about 35 kilometers east of Ouagadougou. Our study focused on the Zagtouli and Nagreongo power plants because they are among the first large solar power plants in our country and are the ones that can provide complete energy production data for a period of at least two years.

2.2. Description of Solar Photovoltaic Power Plants

Inaugurated in 2022, the Nagreongo solar photovoltaic power plant is the result of a public-private partnership between the Burkinabe government and Green-Yellow, a French company based in Saint-Etienne, and the Ouagadougou Solar Energy Production Company. Built on an area of 50 hectares, the plant has a capacity of 30 MWp with an estimated annual production of 49 GWh/year. The PV field consists of sixty-seven thousand eight hundred and seventy-two (67,872) 445 Wp modules connected together in several series/parallel strings. The plant has one hundred and one (101) inverters with a unit capacity of 250 KVA for grid injection. As for the transformers, there are six (06) units, each with a rated power of 4.25 MVA. Their role is to step up the voltage generated by the PV system to a high voltage corresponding to the voltage level of the evacuation line of the National Electricity Company of Burkina Faso, which is 33 kV. The Zagtouli solar power plant was completed and inaugurated in 2017 with a capacity of 33.7 MWp for one hundred and twenty-nine thousand six hundred (129,600) 280 Wp PV modules. It covers an area of sixty (60) hectares and produces more than 50 GWh/year, or approximately 2.5% of annual electricity consumption. There are thirty-two (32) inverters installed, each with a unit capacity of 1.4 MVA fed into the grid, compared to sixteen (16) transformers with a unit capacity of 2.3 MVA also feeding into a 33 kV transmission line.

2.3. Data and Methodology

Each power plant is equipped with SCADA (Supervisory Control and Data Acquisition), which is a real-time control and data acquisition system. The SCADA system is a means of remote data management in these power plants. It consists of controllers, human-machine communication interfaces, a database, and data management software. The information collected by the various sensors on the operation of the power plants is transmitted and recorded on a central unit, allowing the operator to monitor the power plant's facilities and operations. SCADA thus makes it possible to monitor energy production, cell temperature, solar radiation, and the operating status of the solar modules on a daily basis. Meteorological data, including precipitation, temperature, relative humidity, and wind speed, are measured by the synoptic stations of the National Meteorological Agency. It is a set of devices used to make meteorological observations for forecasting or analysis purposes. Based on the global solar radiation (I_r) measured at the Zagtouli and Nagreongo sites, the solar energy potential available on a horizontal plane is calculated using equation (1) following sunrise (L_s) and sunset (C_s) [10, 11]:

$$I_g = \int_{L_s}^{C_s} I_r(t) dt \quad (1)$$

The output of a photovoltaic power plant corresponds to the energy it can supply over a given period, expressed in kilowatt hours (kWh). Estimating this energy output depends heavily on the amount of solar radiation received at the site and can be calculated using the following formula [35, 36]:

$$E_p = I_g \times P_C \times C_p \quad (2)$$

In this equation, P_C represents the peak power of the solar photovoltaic field and C_p a performance indicator for the solar system with values between 0.65 and 0.75. It depends, among other things, on the efficiency of the inverter, the presence of shading or dirt, losses due to cables, and the operating temperature of the solar panels. In addition to in situ measurements, we use satellite observations from the MODIS (MODerate Resolution Imaging Spectro-radiometer) sensor aboard the TERRA satellite, which has been extensively described in several research papers [37, 38]. These data concern the aerosol optical depth (AOD) measured at a wavelength of 550 nm and the Angström coefficient calculated in the spectral band between 412 nm and 470 nm, which are available on NASA's Giovanni website [37]. Indeed, AOD or (τ) is a key indicator, just like atmospheric transparency visibility defined by aerosols, and depends on altitude (z), wavelength (λ) and attenuation coefficient $\alpha_{ext}(z, \lambda)$ according to the following equation (3) [39]:

$$\tau(\lambda) = \int_{\Delta z} \alpha_{ext}(z, \lambda) dz \quad (3)$$

The Angström coefficient (α) is a size parameter that provides information about the nature and origin of particles. It is calculated from the spectral dependence of the optical depth and is expressed by equation (4) below:

$$\alpha = -\frac{\ln\left(\frac{\tau_1}{\tau_2}\right)}{\ln\left(\frac{\lambda_1}{\lambda_2}\right)} \quad (4)$$

In order to better characterize the effect of seasonality on

the energy production of photovoltaic power plants, we calculate Pearson's correlation coefficient (R), which is an indicator ranging from -1 to 1. It allows the linear relationship between two variables (X) and (Y) to be established according to expression 5, where (x_i, y_i) are the individual variables considered and (\bar{x}, \bar{y}) their respective means [39, 40].

$$R = \frac{\sum_{i=1}^n [(x_i - \bar{x})(y_i - \bar{y})]}{\left[\left(\sum_{i=1}^n (x_i - \bar{x})^2 \right) \left(\sum_{i=1}^n (y_i - \bar{y})^2 \right) \right]^{\frac{1}{2}}} \quad (5)$$

3. Results and Analysis

3.1. Interannual Variability of Aerosols

3.1.1. Annual Cycle of Aerosol Optical Depth

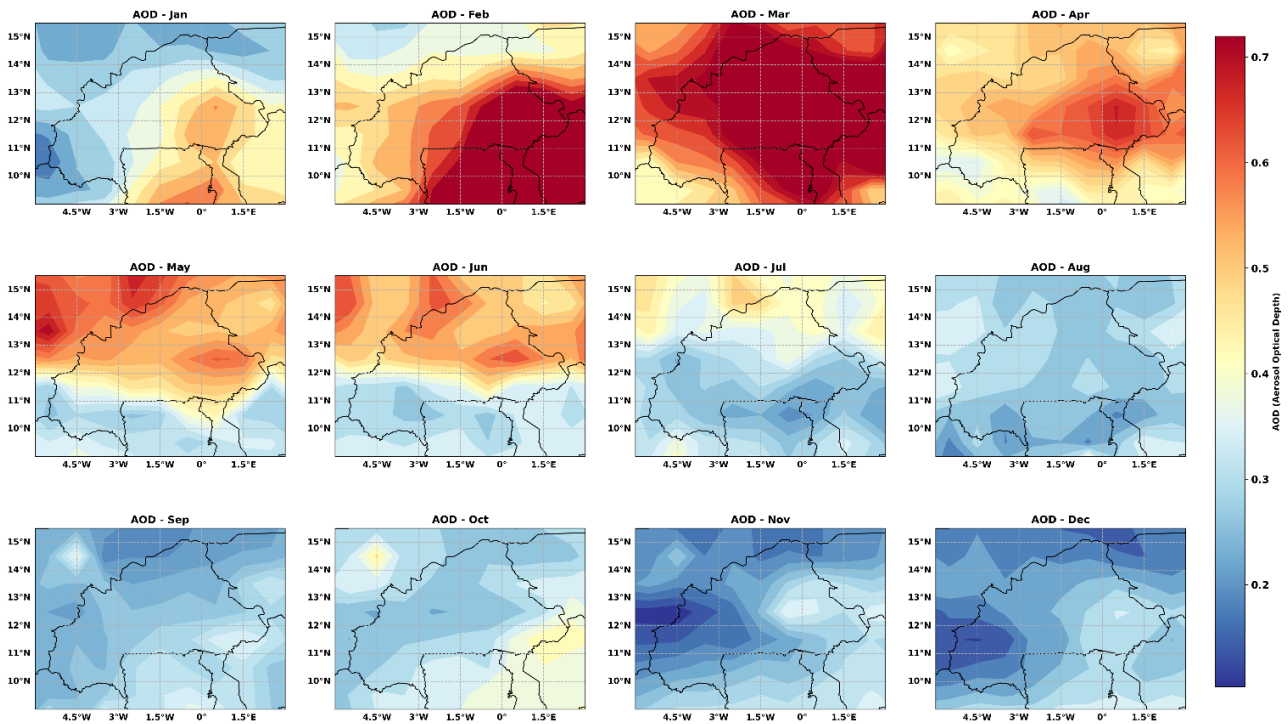


Figure 1. Interannual spatial distribution of aerosol optical depth at 550 nm.

Figure 1 above shows an overview of the interannual spatial distribution of aerosols in Burkina Faso during the period from 2020 to 2024. This representation illustrates the maximum aerosol levels during the winter months of February, spring (March-April-May), and summer in June. This is consistent with the Harmattan wind flow in the Sahel, which is predominant during the dry season, particularly in winter and

spring. The Harmattan is a northeast wind that remains the main vector for the emission, transport, and distribution of atmospheric particles in the Sahel and West Africa in general. Furthermore, it should be noted that the African continent is home to the world's largest sources of mineral dust emissions, mainly located in the Sahara, including the Bodele Depression in Chad, southern Algeria, and the Mali-Mauritania border [41,

42]. All these sources, combined with Burkina Faso's proximity, would explain the high aerosol optical depth (AOD) values characteristic of a highly polluted atmosphere due to the long-range transport of aerosols in addition to local emissions, which are more closely linked to road traffic and biomass combustion from bush fires [43]. Added to this is the fact that vegetation cover is less extensive in Burkina Faso, especially in the north, which is conducive to erosion by surface Harmattan winds, particularly in February, March, and April, when the effect is much more pronounced. It should be noted that during this period, Burkina Faso experiences a high frequency of dust events marked by AOD values above 0.8 and even reaching 2 or 3 [29, 44, 45]. The summer period (June-July-

August) is marked by the monsoon flow, a southwesterly wind laden with moisture that is responsible for rainfall in the Sahel, particularly in Burkina Faso. Thus, this rainy period, characterized by the rise of the intertropical convergence zone north of the equator around 10°N, is marked by very violent convective systems that are responsible for strong wind gusts, which may explain the enormous quantities of aerosols in early summer in June [46]. However, the impact of the rainy season on aerosol emissions is particularly noticeable in summer in August and in autumn (September-October-November), which is a transition period between the monsoon and the harmattan in the Sahel [47].

3.1.2. Annual cycle of the Angstrom Coefficient

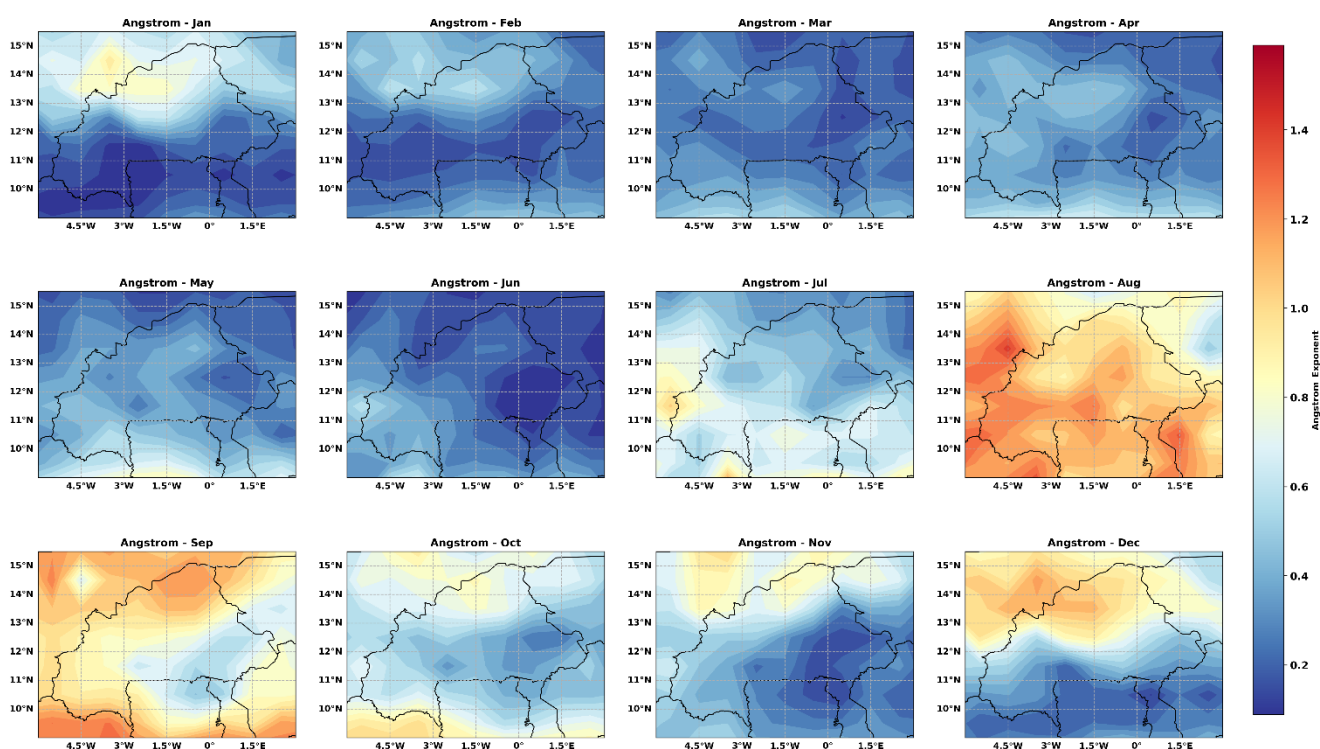


Figure 2. Interannual spatial distribution of the Angström coefficient.

Figure 2 shows the cycle of interannual monthly averages of the Angström coefficient measured in the spectral band between 412 nm and 470 nm by the MODIS sensor over the period from 2020 to 2024. This is an important parameter that provides information on the nature and origin of atmospheric particles. Angstrom coefficient values below 1 indicate a predominance of coarse particles, while values below 1 indicate a predominance of fine particles [47]. To this end, analysis of the annual cycle of the Angström coefficient indicates a predominance of large particles during the winter and spring months, particularly from January to May. In line with wind patterns during the Harmattan season, these aerosols may be associated with mineral dust, which is further justified by the

climatic context of Burkina Faso, located in the Sahel region, which has a semi-arid climate [28]. These coarse mode particles are also visible in summer during June and July due to convective systems, and in autumn during October and November, probably linked to the dynamics of the intertropical convergence zone following the retreat of the monsoon towards the Gulf of Guinea [37]. However, August and September appear to be more influenced by fine-mode particles composed of Aitken particles and accumulation. In fact, fine aerosol particles are caused by the local resuspension of dust due to unpaved roads and long-distance transport in the Saharan air layer. It should also be noted that August is the peak rainy season in Burkina Faso, which limits the effect of mineral dust

due to soil moisture and atmospheric leaching. During this period, the Harmattan is more active in the Sahara, marked by strong thermal depressions due to intense heat. This causes emissions and the transport of fine desert particles at high altitude to the Sahel. Added to this are carbonaceous aerosols emitted locally as a result of road traffic and biomass combustion, especially in winter, particularly in December and January, creating a plume of aerosols dominated by mineral dust [43, 48].

3.1.3. Annual Cycle of Aerosols at the Study Sites

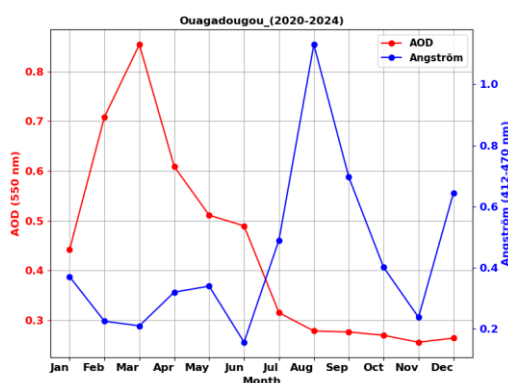


Figure 3. Representation of the annual cycles of AOD at 550 nm and the Angström coefficient measured in the spectral band between 412 nm and 470 nm.

Figure 3 shows the annual cycle of AOD and the Angström coefficient, illustrating the evolution of aerosols in the area where the Zagtouli and Nagreongo solar power plants are located between 2020 and 2024. From January to June, AOD varies between 0.45 and 0.85, indicating a high concentration of aerosols in the atmosphere with a peak around 0.85 observed in March, followed by a considerable decline from July to December. Thus, this evolution of aerosols at sites hosting solar power plants is consistent with the seasonality of aerosols in Burkina Faso, where maximum levels are observed during the winter and spring periods and then in early summer in June, with minimum levels from July to December. However, the minimum Angström coefficient values associated with the AOD maxima at the sites reflect the strong dominance of large particles attributed to desert dust during this period of prevailing Harmattan winds and convective systems, particularly in June. The dominant effect of fine particles indicated by the maximum Angström coefficient values between July and December is probably due to long-range transport, local pollution, and the resuspension of sediments mobilized by rainwater, especially at the end of the winter season [37, 47].

Furthermore, this considerable decrease in aerosols from August onwards highlights the hydrophilic nature of mineral dust particles, which are largely eliminated by sedimentation, especially during the wet season [39]. The calculated correlation coefficient ($R = -0.96$) indicates a strong negative correlation between AOD and the Angström coefficient, which allows us to easily conclude that when AOD increases, the Angström coefficient decreases sharply, and vice versa, illustrating the granulometric nature and origin of the suspended particles.

3.2. Seasonal Impact of Atmospheric Parameters on the Output of Solar Photovoltaic Power Plants

3.2.1. Study of the Seasonal Effect of Aerosol Optical Depth (AOD) on Solar Potential

The two graphs in Figure 4 above show the evolution of AOD and solar radiation at the Nagreongo and Zagtouli sites. An analysis of this data shows very high variability in solar potential at both sites, with peaks observed in spring in March and April for Nagreongo and Zagtouli respectively, and then in autumn in October. These favorable periods for solar potential coincide with periods of high solar activity in the Sahel, particularly in Burkina Faso [11, 12]. In addition, these periods correspond to the spring and fall equinoxes, characterized by minimal solar declination, when the sun's rays reach the Earth's surface directly. However, the minimum potential values obtained in August during the summer period can be explained by the albedo of clouds [49] during this period of monsoon predominance, as well as by the extinction of fine aerosol particles suspended at medium and high altitudes [50]. Furthermore, a combined analysis of the two parameters indicates an inverse relationship between AOD and solar potential during the fall (September, October, November), winter (December, January, February), and spring (April in Zagtouli and May in Nagreongo). The correlation coefficients calculated for Zagtouli ($r = -0.37$) and Nagreongo ($r = -0.49$) confirm this inverse relationship. This highlights the direct effect of aerosols on solar potential through the scattering and absorption of solar radiation at production sites. Although this correlation is weak due to the absolute values of the coefficients, it allows us to appreciate the significant impact of aerosols on solar potential, given the high variability of the aerosol population linked to multiple emission sources. To this end, studies quantifying the effect of aerosols on solar radiation in the Sahel have revealed a significant attenuation of direct solar radiation, leading to a considerable change in the global radiation required for solar photovoltaic conversion [11, 30, 51].

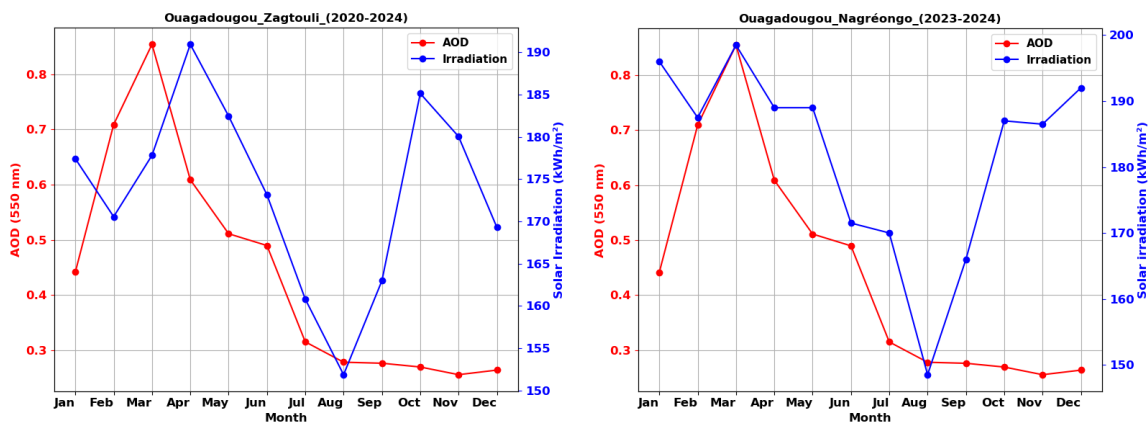


Figure 4. Annual cycle of AOD and solar potential at the Zagtoui and Nagreongo sites.

3.2.2. Study of the Seasonal Effect of Aerosol Optical Depth (AOD) on Solar Photovoltaic Production

The annual cycle of solar photovoltaic production and the AOD of the two power plants is illustrated in Figure 5. It reveals significant variability in solar photovoltaic production depending on the period and season at the study sites. Indeed, this representation clearly illustrates the production peaks at the Zagtoui site during the winter months of February, March, and May in the spring, and then in October and November during the autumn. These production peaks at the Nagreongo site occur in the autumn months of October and November, in the winter months of December and January, and then in the spring months of March and May. However, the correlation coefficients calculated around the values $r = -0.29$ and $r = -$

0.36, respectively for the Nagreongo and Zagtoui power plants, show an overall opposite trend between AOD and solar photovoltaic production. This negative correlation, although weak, highlights the significant dependence of energy production from solar photovoltaic power plants on the atmospheric aerosol load defined by AOD. This impact is corroborated by the coincidence of minima or maxima between the two cycles, particularly in May, June, July, and autumn at the sites. In addition, it should be noted that solar photovoltaic production is directly linked to the availability of solar potential, which undergoes enormous changes depending on the state or transparency of the atmosphere, especially during dust events [30]. However, the AOD peaks and production in March at both sites are likely due to maintenance of the power plants, which includes cleaning the surface of the modules following aerosol deposits, especially during this period of dust events.

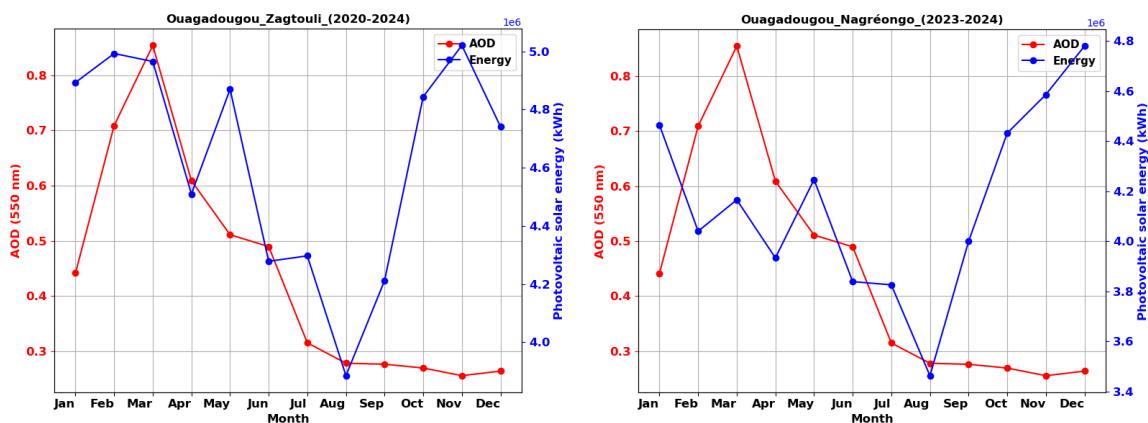


Figure 5. Annual cycle of AOD and solar photovoltaic production at the Zagtoui and Nagreongo sites.

3.2.3. Study of the Seasonal Effect of Irradiation on Solar Photovoltaic Production

The evolution of the annual cycle of irradiation and solar production at the Nagreongo and Zagtoui power plants is

shown in Figure 6. This representation clearly shows a good correlation between the annual cycles of irradiation and the energy produced by the power plants, especially at the Nagreongo site, thus justifying the importance of solar potential

availability on the electrical performance of a solar photovoltaic system. All this is corroborated by the positive values of the correlation coefficients calculated at the Zagtouli and Nagreongo sites, which are $r = 0.68$ and $r = 0.82$, respectively. However, this positive impact of irradiation may be skewed by other climatic factors acting as a modulating factor that dissociates the absolute production peaks of the two power plants. Added to this is the irregular cleaning of the surface of the modules, which can cause a drop in production, especially during the Harmattan season, due to the effect of mineral dust,

as indicated by the April production Figures at the Zagtouli site, despite the high solar potential during this period. Furthermore, the effect of aerosol deposits on the surface of the modules depends on their particle size, as the aerosol layer coating is more opaque to incident radiation than when the sediments are small [52]. In addition, the impact of the monsoon is clearly visible in August, which is marked by minimum values for irradiation and power plant production due to the albedo of clouds and the extinction of fine aerosol particles.

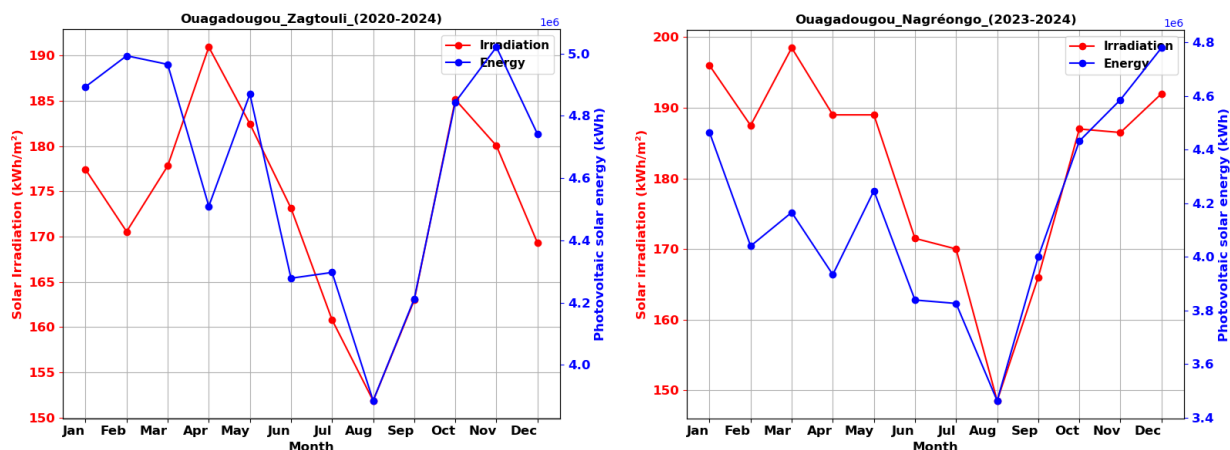


Figure 6. Annual cycle of irradiation and solar photovoltaic production at the Zagtouli and Nagreongo sites.

3.2.4. Study of the Seasonal Effect of Temperature on Solar Photovoltaic Production

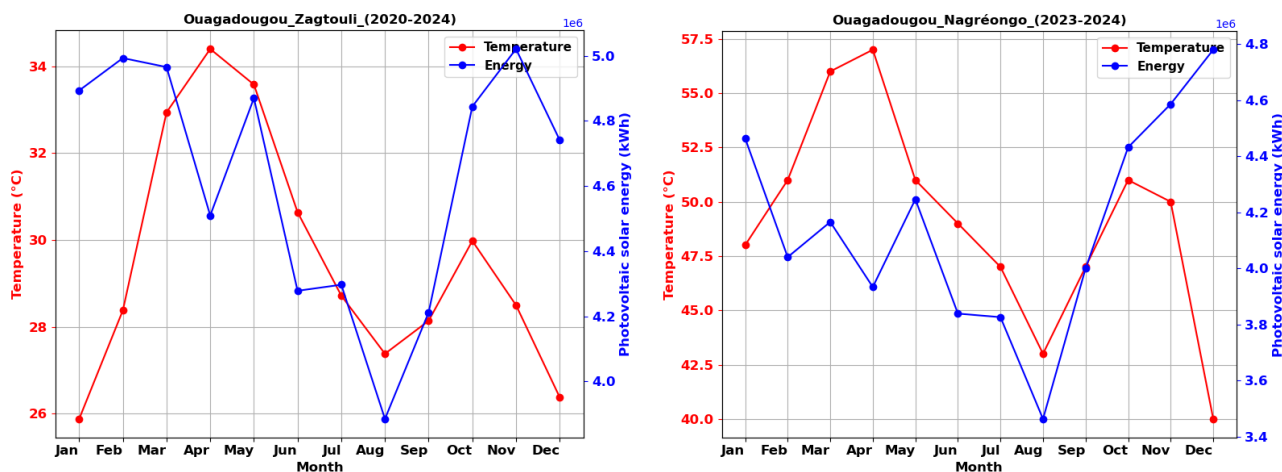


Figure 7. Annual cycle of temperature and solar photovoltaic production at the Zagtouli and Nagreongo sites.

Figure 7 above illustrates the interannual evolution of solar power plant production and temperature at the Zagtouli and Nagreongo sites. It clearly shows the maximum temperatures in spring and autumn, with peaks observed in April and October. This temperature variability is corroborated by the annual cycle of solar potential, which reaches its minimum in August,

a period of heavy rainfall. It should be noted that the temperature of the air or PV systems is governed by solar activity, which remains the main source of energy responsible for warming the different layers of the atmosphere according to the seasons and periods. Thus, the performance of a solar photovoltaic system depends largely on the temperature of the PV

cells, which is directly linked to the ambient temperature and solar radiation [52]. Added to this is the direct effect of black carbon-rich aerosols, which are mainly absorbent [53]. These anthropogenic particles, caused by human activity, behave like greenhouse gases and can contribute significantly to the increase in air and photovoltaic cell temperatures. Furthermore, an assessment of the correlation between the two variables shows negative values for the coefficients, which are $r = -0.16$ and $r = -0.19$ respectively at the Zagtoui and Nagreongo sites. This reverse trend, although slight, illustrates the negative impact of temperature on solar photovoltaic conversion. This influence is particularly noticeable in April, which saw a drop in production despite the high solar potential during this spring period. The period from June to August corresponds to the rainy season, which brings lower temperatures and less solar radiation, explaining the decline in production despite falling temperatures. From August to December, we see a slight rise in temperature, while production increases sharply, peaking in November for Zagtoui and December for Nagreongo. During this phase, temperatures drop from October onwards to relatively low levels, creating favorable conditions for energy production. In addition, this period is characterized by atmospheric conditions in which the presence of aerosols is almost negligible due to low AOD values, which could result in good levels of sunlight for optimal production by solar power plants.

3.2.5. Study of the Seasonal Effect of Relative Humidity on Solar Photovoltaic Production

The annual cycle of relative humidity and solar production at the two power plants is shown in Figure 8. Looking at this

Figure, we can see a significant inverse relationship between humidity and solar production. Overall, they show two major trends: an upward trend and a downward trend. For relative humidity, the increasing phase is observed from January to August, with a peak in August at around 82%. Meanwhile, energy production showed an overall downward trend, reaching its lowest point in August at both power plants. This downward trend in production can be explained, on the one hand, by a more hazy atmosphere marked by a high concentration of aerosols, particularly during the period from January to April, in line with the AOD cycle. On the other hand, it could also be due to high humidity accompanied by cloud cover, reflecting a high water vapor content in the atmosphere, which reduces the intensity of solar radiation, especially during the period from June to August. It should be noted that water in the form of vapor and clouds is a powerful absorber and diffuser of incident solar radiation, which explains why production drops when humidity increases [54, 55]. Also, during the dry season, dust settles on the PV modules and when this humidity sticks these particles to the glass of the modules, it acts as an opaque layer that also reduces the radiation transmitted to the solar cells, but also causes corrosion of the modules. Then, from August to December, there is a sharp decrease in relative humidity, while energy production begins to rise sharply, reaching its peak in December for Nagreongo and in November for the Zagtoui site. This period marks the gradual end of the rainy season, leading to a decrease in relative humidity, which promotes the return of clear, sunny skies. This inverse relationship between relative humidity and PV power plant output is also supported by the correlation coefficients, which are $r = -0.6$ and $r = -0.43$ for the Zagtoui and Nagreongo sites, respectively.

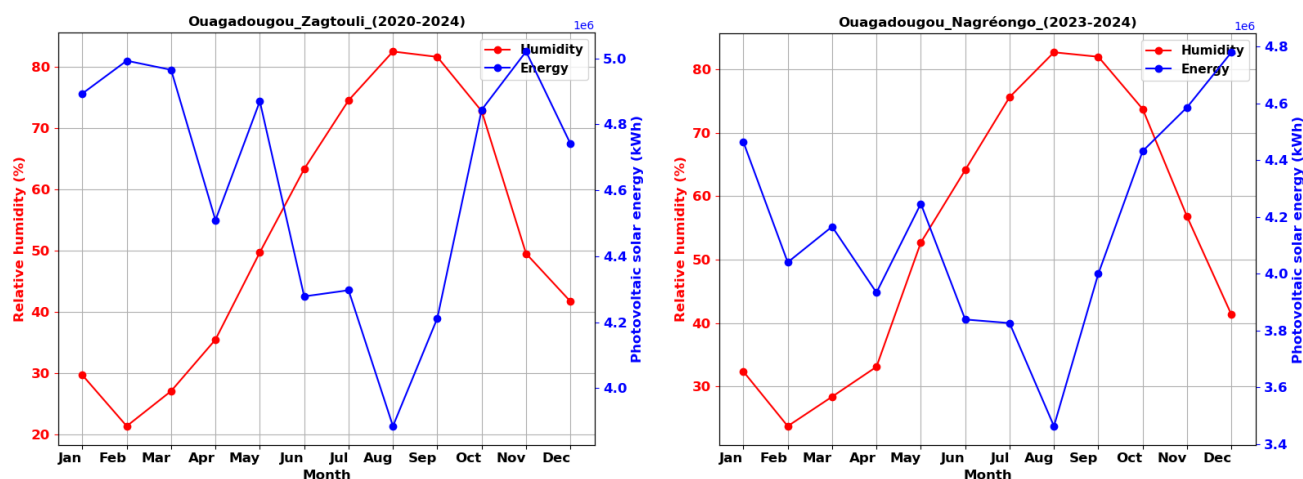


Figure 8. Annual cycle of relative humidity and solar photovoltaic production at the Zagtoui and Nagreongo sites.

3.2.6. Study of the Seasonal Effect of Wind Speed on Solar Photovoltaic Production

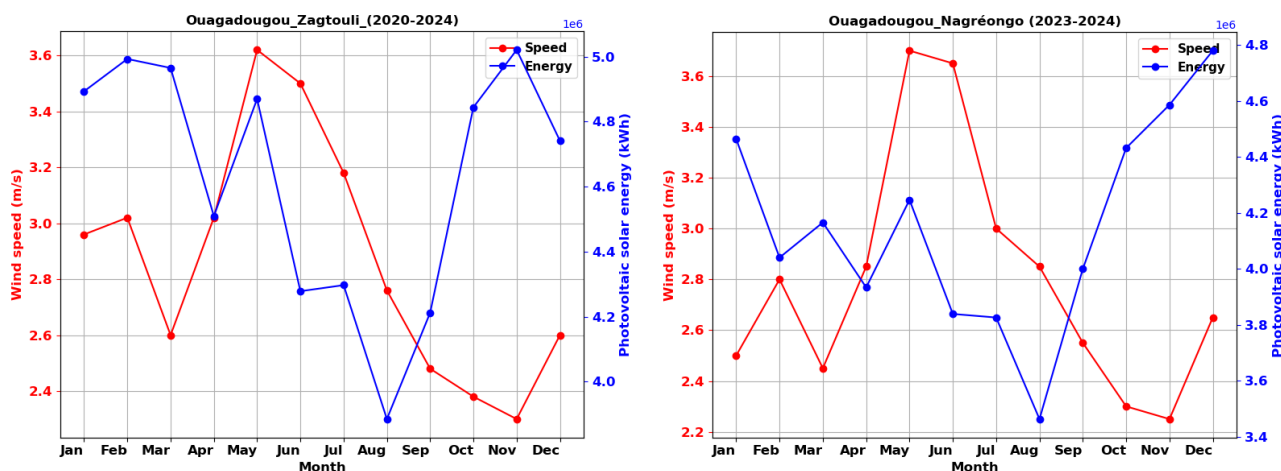


Figure 9. Annual cycle of wind speed and solar photovoltaic production at the Zagtouli and Nagreongo sites.

Figure 9 above shows the graph of energy production and wind speed at the Nagreongo and Zagtouli power plants. Analysis of the Figure shows that wind speeds peak in February during winter and in May and June at the beginning of summer. These peaks are due to the predominance of northeasterly winds, particularly during the Harmattan period, and this flow, combined with the high solar potential during the spring, very often causes strong atmospheric circulation from the ocean to the continent, resulting in remarkable wind speeds in May and June, in addition to the influence of convective systems at the beginning of the monsoon season. Furthermore, the retreat of the monsoon and the importance of vegetation cover in September, October, and November are reflected in the minimum wind speeds during this transition period. It should be noted that wind can have a dual effect on the operation of solar photovoltaic systems. During periods of high temperatures linked to sunshine, wind circulation helps to dissipate heat from solar production systems, thereby lowering the temperature of photovoltaic cells. This phenomenon is favorable for PV power plant production, especially during the spring period, as illustrated by the energy peaks in May. However, wind causes mineral dust to be emitted, which settles on the surface of photovoltaic modules and reduces the transmission of radiation to solar cells. This is the case during the Harmattan season in March, which is characterized by minimal wind activity and favorable conditions for solar power generation at both sites. This observation is also visible in December at the Zagtouli power plant and in January at the Nagreongo site. In addition, the impact of aerosols is related to their size, as fine particles occupy more of the surface of the modules than coarse particles and form a more opaque layer that acts as a barrier to the penetration of solar rays [52]. These analyses show that wind often has contradictory effects (cooling and dust), justified by production peaks associated with minimum wind speeds and vice versa. However, wind has a predominantly favorable effect, as illustrated by the positive correlation

coefficients calculated around $r = 0.20$ for the Zagtouli site and $r = 0.15$ for the Nagreongo site.

4. Conclusions

Photovoltaic solar power generation is difficult to predict due to its intermittency, which is closely linked to environmental factors that vary with climate and location. This study therefore provided an opportunity to assess the effects of atmospheric parameters such as aerosol pollution, solar radiation, temperature, relative humidity, and wind speed on the performance of the Zagtouli and Nagreongo solar power plants located in the central region of Burkina Faso, more specifically in the municipality of Ouagadougou. This analysis made it possible to characterize the seasonality of aerosols at both large and local scales across the study sites, in order to better understand the impact of seasonal dynamics on aerosol emissions under the strong influence of desert dust. Furthermore, after highlighting the variability of climatic variables, a correlation study based on qualitative analysis helped explain the production cycle of the solar power plants, which depends strongly on environmental and climatic conditions. However, it remains necessary to quantify the impact of atmospheric parameters through new approaches based on in situ measurements and simulation models in order to achieve better optimization of photovoltaic solar systems in Burkina Faso and across the Sahel region in general.

Abbreviations

AOD	Aerosol Optical Depth
MODIS	MODERate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration

PV Photovoltaic
SCADA Supervisory Control and Data Acquisition

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Data Availability Statement

For this work, we use data from the MODIS sensor aboard the Terra satellite, available on NASA's Giovanni website (<https://giovanni.gsfc.nasa.gov/giovanni/>). In addition, we use meteorological and photovoltaic power plant production data available upon request from the National Meteorological Agency and the Ministry in charge of Energy of Burkina Faso.

Conflicts of Interest

The authors declare that they have no competing interests.

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