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Statistical Studies for the Evaluation of Solar Radiation in a Cloudy Context for Photovoltaic Production in Senegal

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Abstract To integrate the parameter related to sky cloud cover in the modeling of photovoltaic production systems and to study the effects due to solar fluctuations, a model is implemented and validated on the basis of data produced by a radiometric station. The goal is to make simulations more reliable in this area where solar radiation is the most significant input parameter because many of the data sources used are theoretical and do not reproduce its real profile. This study will solve this problem by reproducing the fluctuations of the level of sunshine, which generate many effects to the disadvantage of the penetration of photovoltaic systems in the electrical networks.

Keywords Cloud cover, solar radiation, Octas, photovoltaic production

Introduction

Clouds are key components of the climate and are therefore an element to be considered in the field of research in renewable energies. Photovoltaic production is strongly related to the level of sunshine compared to other input parameters such as temperature and wind speed. The intensity of sunshine in turn varies substantially depending on the cloud cover of the sky. The very frequent presence of the clouds and their dynamics in the sky thus imposes the taking into account of their effect on the irradiation. Indeed, at any given moment, about half of the Earth is covered with highly dynamic clouds in relation to atmospheric circulation. The irradiating properties of clouds make them key components of the Earth's energy budget and hence solar energy [1].

In many researches, it is customary according to the geographical position of the site, the season and the time, to use the global irradiation data provided by specialized software, whereas considerable differences are noted between these data and those measured on the site for a given day, and according to the study the fluctuations are not present.

The present work consists in the modeling of the phenomenon of cloud in order to take it into account in the simulations of photovoltaic production of the plants being installed and planned on a dozen different sites in Senegal by 2028. This integration is all the more important as the effects due to the fluctuations and intermittences of electricity production in the network are precisely studied.

Materials and Methods

The choice of the method for determining overall irradiation at a site is highly dependent on the availability of weather data over a significant period. It also depends on the application to use the main input data that will be sunshine. For developing countries, there is a lack of detailed data in this area over an extended period of decades. Hence the success of methods based on cloud cover available on specialized websites and covering the whole planet. Two approaches have emerged and adopted in several research projects.

Statistical approach

According to Ayu Wazira AZHARI et al. [2], the statistical approach for estimating solar radiation can be classified into three categories:

- Cloud-based models (Fritz et al., 1967 [3]; Nielsen et al., 1981 [4]; Exell, 1996 [5], Supit and van Kappel, 1998 [6], Mefti et al., 2008 [7]),
- Models based on sunshine (Angström 1924 [8], Prescott 1940 [9], Togrul 2000 [10], Ertekin 2007 [11])
- Temperature-based models (Bristow and Campbell 1984 [12], Thornton and Running 1999 [13], Meza and Varas 2000 [14], Weiss and Hays 2004 [15]). .

Statistical models are based on empirical relationships between information's collected on satellite data or simple ground observation. These approaches are simpler and do not require precise information on the composition of the atmosphere.

Theoretical approach

The theoretical approach is not suitable for most researches because it is more complex and requires precision processing of image data and auxiliary meteorological data such as air pressure, presence of vapor water, the physical property of aerosols…. Gautier et al. (1980) [16], Moser and Raschke (1983) [17], Malik et al. (1997) [18], Ehnberg and Bollen (2004) [19] and Azhari et al. (2008) [20] are among the few researchers who use this method to determine solar radiation.

Model taking into account astronomical effects and atmospheric effects

Ehnberg & Bollen (2005) [19] have developed a more stochastic model to simulate global solar radiation on a horizontal surface. This model is specifically designed for use in power system reliability calculations. This model is made taking into account astronomical effects and atmospheric effects on the amount of solar radiation received. In this model, the astronomical effects are due to the rotation of the earth around the sun and the rotation of the earth around its axis which will affect the seasonal and daily variations of solar radiation.

The equation giving the expression of the vector of solar declination angle δ_s is presented below:

$$\delta_s = \Phi_r cos\left[\frac{C(d-d_r)}{d_y}\right] \quad (1)$$

where d (rad) is the index of the day of the simulation,

$C = 2\pi$(rad),

$\Phi_r = 0{,}409$(rad) is the inclination of the axis of the earth with respect to the orbital plane of the earth around the sun,

d_r the index of the day of the year at the summer solstice, June 22 for the non-leap years,

et d_y the number of days in the year of the simulation.

The local elevation angle Ψ over a period determined by d (rad) is given by the following relation:

$$sin\Psi = sin\phi sin\delta_s - cos\phi cos\delta_s cos\left[\frac{C.t_{UTC}}{t_d} - \lambda_e\right] \quad (2)$$

where ϕ is the positive north latitude of the site,

t_{UTC} (h) the time in Coordinated Universal Time,

t_d (h) the time of the simulation,

And λ_e the longitude of the site, positive west of Greenwich.

The global radiation in a cloudy context G, which constitutes the atmospheric part of the model, is expressed by the relation below:

$$G = \left[\frac{a_0(N)+a_1(N)sin\psi + a_3(N)sin^3\psi - L(N)}{a(N)}\right] \quad (3)$$

Where L, a, a_i *(i=0,1,3)* are empirical constants expressed in W/m^2

And *N* the level of cloud cover based on a scale of 0 to 8 (Octas scale [21]).

In the case where $\psi < 0$ ou $G < 0$, the value of G is reduced to 0.

Depending on the level of cloud cover *(N)*, the values of the empirical constants are given in Table 1.

Table 1: Empirical coefficients for the determination of global radiation

a_0	a_1	a_3	a_0	L
-112.6	653.2	174	0.73	-95
-112.6	686.5	120.9	0.72	-89.2
-107.3	650.2	127.1	0.72	-78.2
-97.8	608.3	110.6	0.72	-67.4
-85.1	552	106.3	0.72	-57.1
-77.1	511.5	58.5	0.7	-45.7
-71.2	495.4	-37.9	0.7	-33.2
-31.8	287.5	94	0.69	-16.5
-13.7	154.2	64.9	0.69	-4.3

Implementation of the cloud cover model

On the one hand, the Ehnberg & Bollen model [19] was initially used to determine the vector of solar declination angles over a given period for each of the ten sites that already have or will have a photovoltaic power plant. This is the astronomical part of the model as described above. With respect to the atmospheric part of the model, the relationship between global radiation and cloud cover was used to generate the overall radiation at each site by typical day of each month of the year.

We obtain by this method a file containing, for each site, the global radiation received in configurable cloud conditions. This will allow our program to call this file with as an input parameter the cloud cover based on the Octas scale (from 0 to 8).

On the other hand it was a question of determining by a statistical method the probability relative to the cloudy context of each geographical site according to the season, more precisely the day of the year. A map collection campaign with a cloud layer was therefore conducted on the map publishing application named WoldView.

As an example on the Bokhol site (14 ° 27'30 "North, 16 ° 51'54" West), we show in Figure 2 the curves representing the global radiation on day considering a constant level of cloud cover by curve over the period, with for each curve a given cloud level on the Octas scale.

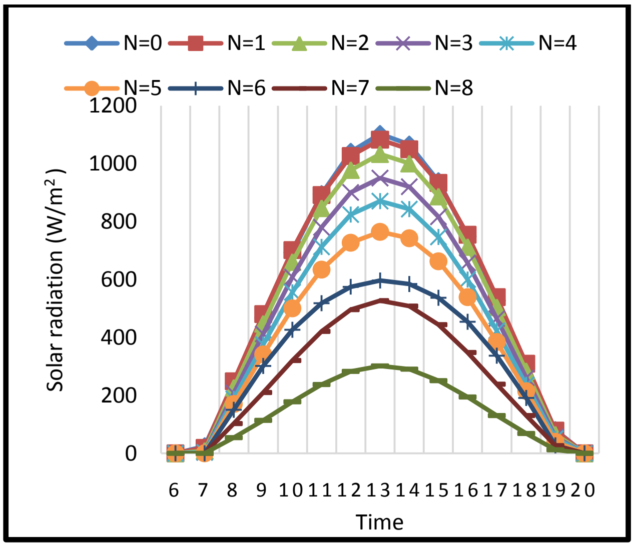

Figure 1: Solar radiation values by coverage level according to the Octas scale at the Bokhol site as of July 23th, 2018

We note that with this model, the level of sunshine can be divided by more than 4 for maximum cloud cover.

Once the overall radiation estimated from the cloud cover index, the random behavior of the sunlight level should be integrated into it, so that the transitions observed in the measurements are simulated. We can therefore consider a statistical term ε determined by a law of normal distribution around the hourly mean of the global radiation as expressed by the equation (4).

$$G_{al} = G + \varepsilon \quad (4)$$

With G_{al} global radiation integrating random behavior

Thus for each hour the variation of the overall radiation can be produced using the value of G calculated and representing a mean over the hour, the distribution based on the standard deviation.
To estimate the mean and standard deviation of cloud cover for a given site for a given period of the year, a statistical study was conducted covering an 18-year period, the purpose being to determine the probable coverage index and apply it in energy production simulations. A collection of climatological data was therefore conducted.

Collection of cartographic data and analyzes

The data collection phase of each geographic site to host solar fields consists of the recovery of the map of Senegal on which is superimposed the cloud layer following the selected day. The NASA Worldview application has been used for this purpose.
The maps extracted from January 2nd, 2001 to November 6th, 2018 at the rate of 4 images per month uniformly distributed over the period, a total of 856 images that tell us about the cloud cover of this day. Figure 3 shows the appearance of the images collected in a synthetic way.

a *b* *c*

Figure 2: Sample of images collected on Wordview (scale: 1 / 18,25,106):
a) January 1st, 2001; b) December 16th, 2004 ; c) April 9th 2011

According to P. A. JONES [22], the cloud cover for a given area cannot be adequately described simply by the mean value for that season or time of day. The way in which cloud presence varies around the mean should also be taken into account. The distribution of the observed values (in Octas or tenths) shows the magnitude of this variation, from a U-shaped distribution with a strong variation to a central-top distribution with a small variation. This can be described by the standard deviation of the observed values or, as used in its work, the standardized standard deviation by the largest possible value for this average cloud.
Each map collected and thus processed to distinguish the pixels representing the clouds of the basemap, so that the mean in terms of cloud cover and the standard deviation giving the shape of the distribution is extracted and recorded (figure 3). ImageJ software [23] was used for this treatment.

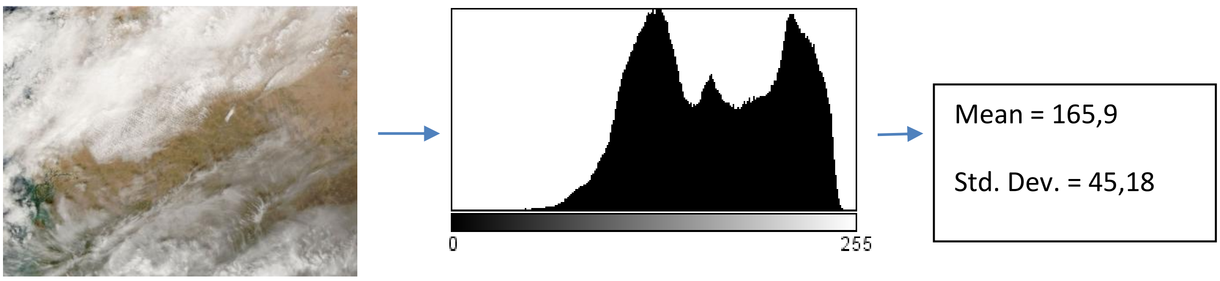

Figure 3: Image processing process for generating mean (on a scale of 0 to 254) and standard deviation

The mean represents the level of the population of whitish pixels representing clouds. The correspondence between the cloud cover rate and the Octas scale is shown in Table 2. This correspondence is obtained by observation.

Table 2: Correspondence table between the cloud cover rate and the Octas index

Cloud Cover Rate (TCN)	Octas scale
TCN<130	0
130≤TCN<145	1
145≤TCN<160	2
160≤TCN<175	3
175≤TCN<190	4
190≤TCN<210	5
210≤TCN<220	6
220≤TCN<250	7
TCN> 250	8

To complete the process, we developed the algorithm used to determine the elements of probability of occurrence of cloud cover indexes for each site per day and per hour. This algorithm is then used for estimating global radiation and then energy production at the 10 sites where it is planned to install the photovoltaic plants in Senegal. A macro developed under Visual Basic for Application calling another macro implemented under ImageJ (for image processing) is used throughout the process.

Description of the radiometric station of the LaSTEE laboratory

To validate the model described above, a radiometric station (figure 4) was installed at the Laboratory of Water and Environmental Sciences and Techniques (LaSTEE) of the Polytechnic School of Thies in Senegal. The platform consists of the measurement devices described below:

- An SP-LITE pyranometer, for measuring global radiation on a horizontal plane;
- A pyranometer of SP-LITE type, for measuring global radiation on a mobile plane supported by a solar tracker named STR-21G;
- A YOUNG model 05103 anemometer, for the measurement of wind speed and direction;
- A PT100 temperature sensor for measuring the outside temperature.

All systems described above are connected to a CAMPBELL SCIENTIFIC model CR1000 data acquisition system. This is connected via RS232 interface to a computer in which the PC400 data logging software is installed. This data is collected daily and continuously in five minutes.

a *b* *c*

Figure 4: Radiometric station of the LasTEE laboratory
a) Overview, b) CR1000 controller, c) Solar tracker

We present in Figure 5 an extract of the radiation data recorded by the station for the day of 17 July 2018. The geographical location of the station corresponds to latitude 14 ° 47'41"N, longitude 16 ° 57'59"W and the altitude 87 meters.

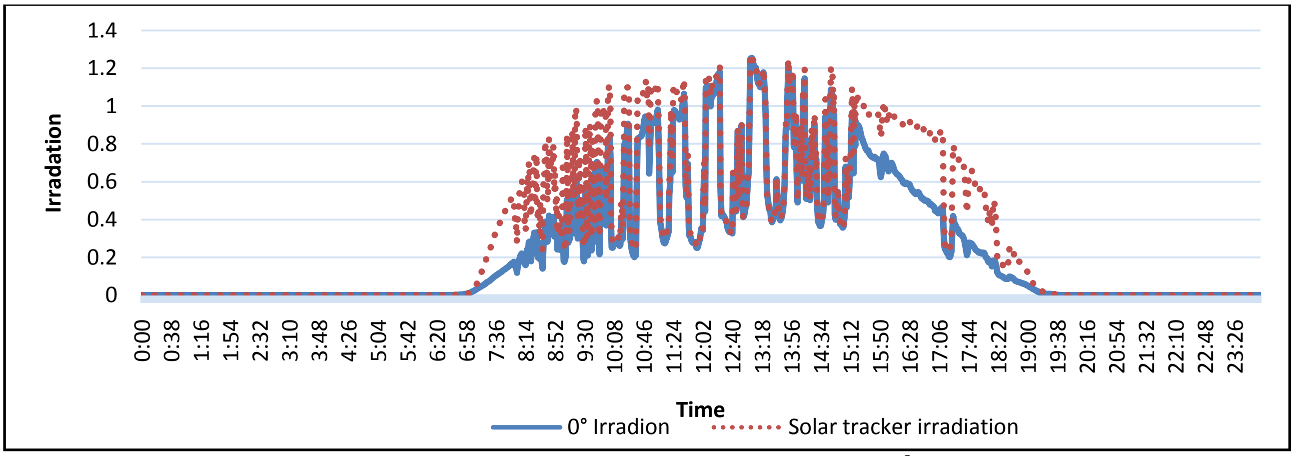

Figure 5: Solar irradiation day of August 25, 2018 (kW/m^2)

Results and Discussions

The model thus developed makes it possible to generate solar radiation data on each site based on geographical location, season and time, and cloud conditions based on a probability derived from statistics.

To validate this model, a campaign of sunshine measurements was carried out on the site corresponding to that of the radiometric station presented previously. These measurements are compared with the data produced by the model simulating the same day with as input the cloud level observed in the maps taken on WorldView.

In Figures 6, 7 and 8we can observe the profile of radiation measured and the one produced by the model for a sample of days with different cloud cover.

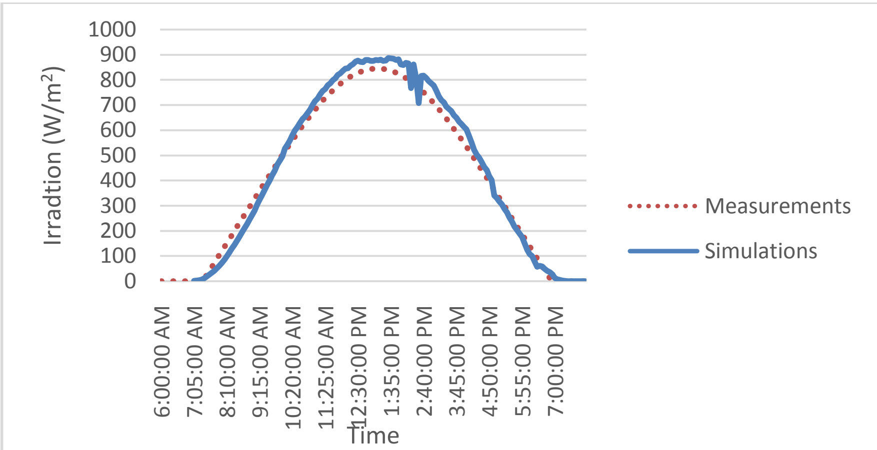

Figure 6: Daily radiation of September 15th, 2019 (clear sky)

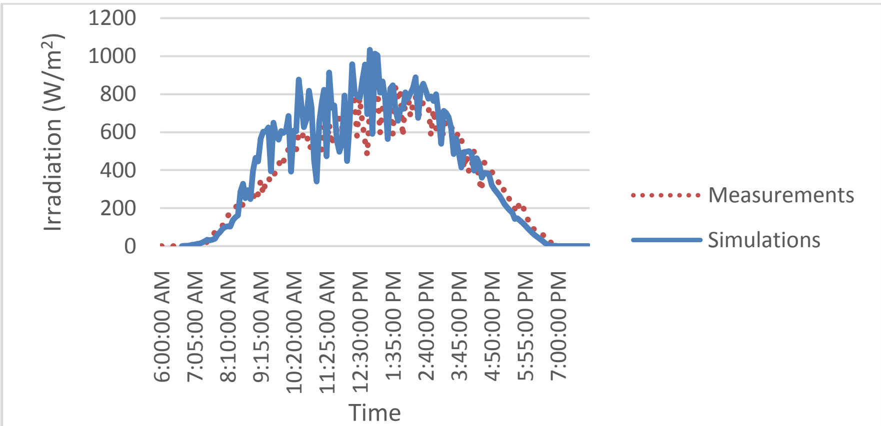

Figure 7: Daily radiation of September 9th, 2019 (cloudy sky)

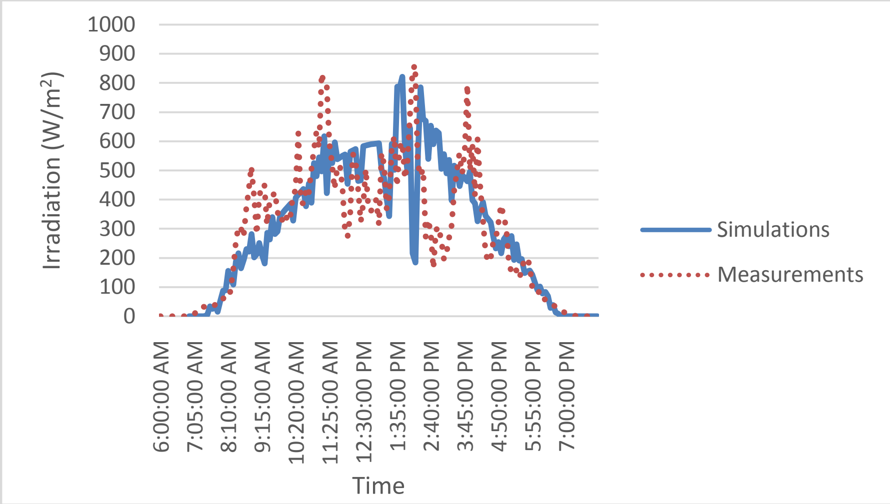

Figure 8: Daily radiation of September 8th 2019 (very cloudy sky)

We can observe in the figures presented below the differences between the results of the different simulations and the measurements made on the site. The evaluation of these errors in different contexts is presented in Table 3. Moreover, the profile of the simulated radiation presents the same types of transitions with more or less the same amplitudes as the measurements, which is decisive for the work in relation to the fluctuation phenomenon of the photovoltaic production.

Analysis of simulated radiation in different cloud conditions

The model developed was used according to three different climatic contexts namely a clear sky, a moderately cloudy sky and a very cloudy sky. The profile of the daily radiation is compared with that of the measurements carried out over the same period on the one hand, but also these simulated data were compared with those generated by the platform for estimating the level of sunshine PVGIS. Table 3 summarizes all the differences between these different data.

Table 3: Comparison of simulation data with measured data and data generated on PVGIS

	Clear sky 15/09/2018 (W)	**Relative error (%)**	**Cloudy 09/09/2018 (W)**	**Relative error (%)**	**Covered 08/09/2018 (W)**	**Relative error (%)**
Simulated radiation	5838.95	2.7	5138.9	9	4158.3	2.9
Mean radiationfrom PVGIS	5628.5	6.3	5628.5	3.9	5628.5	3.9
Clear sky radiation from PVGIS	6685.75	11.3	6685.75	18.3	6685.75	65.5
Measured radiation	6006.75		5650.58		4040.3	

We can see a clear improvement in the use of this new model compared to the theoretical data in the quantification of the global energy produced on a day but the most important is the reproduction of the phenomenon of fluctuation necessary for future work.

Analysis of simulated cumulative photovoltaic production of a cloudy day on the ten sites

For a very cloudy day over the whole territory, the simulation of the results presented below shows a production per site with large fluctuations that are not predictable by the meteorological services that can only inform about the general trend. The purpose of this simulation is to show that globally these fluctuations are able to compensate for each other given the geographic dispersion of the sites. Thus, it is presented in figure 9 the production for some sites among the dozen and the global production on the national territory.

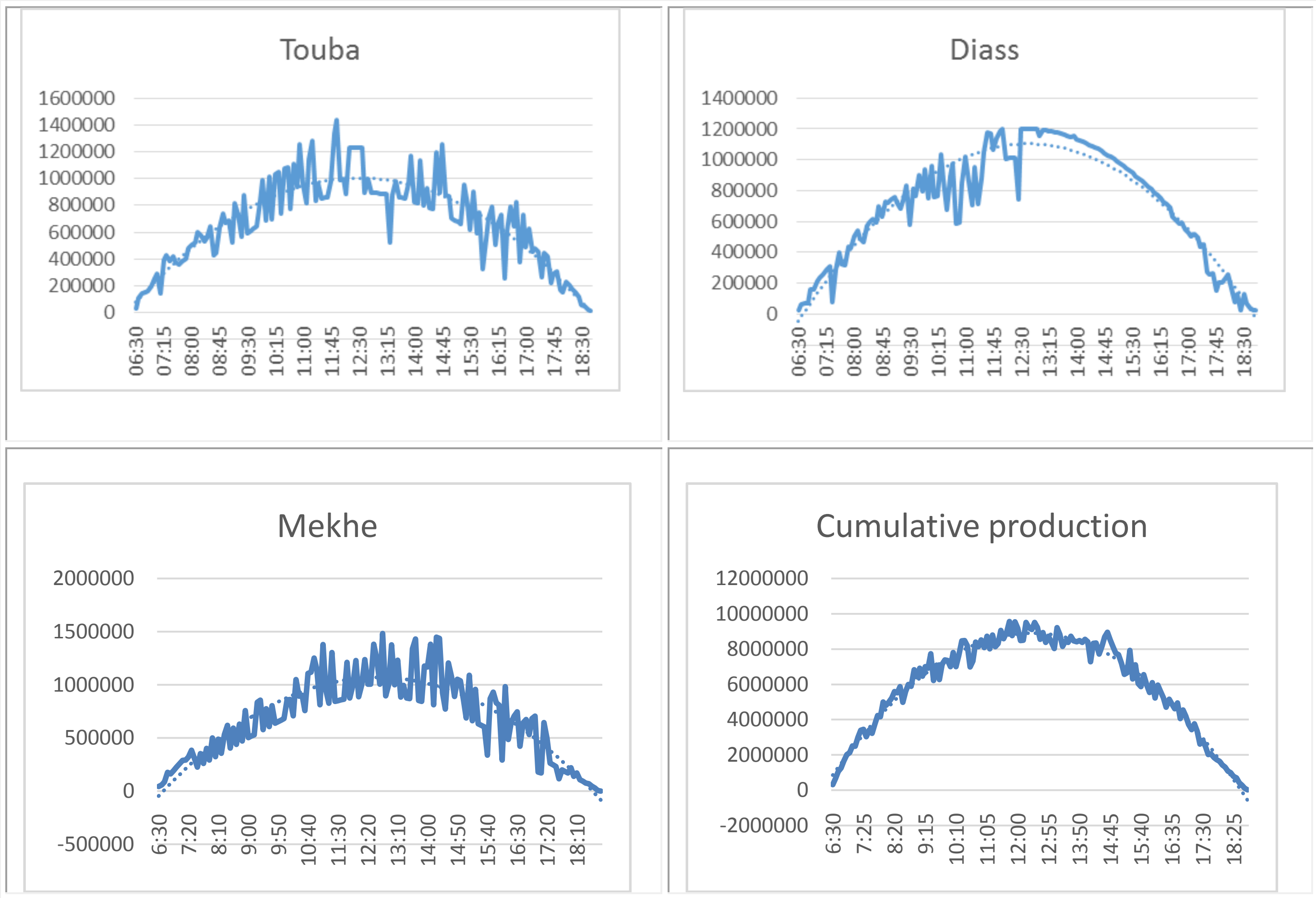

Figure 9: Examples of production simulation of one park by site and profile of overall production (W)

Table 4 shows the differences between the production data calculated on the basis of the daily forecasts that can be provided by the meteorological services per site and globally.

Table 4: Comparison of average absolute errors in percentage between the production of the sites and those of the overall production

Site	Mean Absolute Percentage Error	Site	Mean Absolute Percentage Error
Bokhol	21%	Diass	19.08%
Diamniadio	16.84%	Malicounda	20.23%
Tobene	17.62%	Kahone	17.88%
Mekhe	22.56%	Niakhar	19.76
Touba	49.22%	Sakal	20.38%
Cumulative production	10.15%		

The results indicate that there is a real benefit to be gained from the dispersion of production plants in the choice of sites outside the energy potential, which is a no less important parameter in the choice of installation sites. Fluctuations from a global point of view are clearly less important (around half) and make it possible to better control the photovoltaic production by mobilizing a less significant compensation energy from conventional generators.

Conclusion

In this study it was discussed to develop a tool for the estimation of sunshine on the sites planned to host photovoltaic power plants connected to the Senegal grid. This work was necessary especially since the sunlight estimation data used so far were theoretical and are presented as means in time steps (15 minutes). As a result, some of the issues involved in the penetration of PV systems in power grids could not be studied on this basis, since the two main levers are the fluctuating and intermittent behavior of the solar resource. A statistical method has been used with the advantage of its simplicity and the fact that it is very adapted to countries in which the climatic data specific to each studied site and spread over tens of years are not available.

The fluctuating behavior of the radiation according to different cloud covers could be produced but without being able to faithfully follow the measured profile. This last point was not the objective of the model, it is important to specify that this one is not a tool of prediction of the sunshine, which would require other input data like the cloud cover to closer times for a short-term forecast.

Overall, in addition to the fluctuating behavior that we have come to represent, the daily estimate of received energy has fewer errors than estimated by the online application often used.

This model could be improved by completing the study by taking into account the seasonality of the wind direction at the altitude corresponding to that of the clouds. This would bring simulated fluctuations closer to those measured. Also layers of maps taken with a shorter time step (from one to four hours) could contribute to a more faithful reproduction of sunshine taking into account the cloud cover.

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