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Experimental and Numerical Study of the Effect of Cloud Cover on the Electrical Performance of Photovoltaic Plants

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Abstract

The production of electricity from the sun mainly consists of transforming the light emitted by the sun into electrical energy through photovoltaic cells. This production varies proportionally with the light that illuminates the solar photovoltaic module. According to the literature, we noted that during the period of cloudy passage, the production of the solar modules could see a fall going from 5 to 60% according to the size of the photovoltaic fields. The present work consisted of studying the impact of cloudy passages on the electrical production of PV fields at four sites (Loumbila, Sandogo, Ouaga 2000 and IRSAT). To achieve this, a theoretical and experimental study was conducted. The simulation results were compared to the experimental results of two daily sunshine profiles (sunny and cloudy). The results show significant differences between the experimental and simulated data for the two sunshine profiles considered. The losses of electrical production generated by these cloudy passages vary from 27 to 32% and from 35 to 52%, respectively, for the simulated and experimental results. These differences were explained by the probabilistic character of the cloudy passages and by the fact that other major parameters (aerosols, dust deposits and ageing of the solar modules) were not considered. As perspectives, we recommend a continuation of the work by studying, in addition to the cloudy passages, the influence of aerosols and dust deposits on the PV fields realized by us.

Keywords: Energy, photovoltaic field, performance, modelling, impact, cloud cover

1. Introduction

Energy remains an essential factor in the socio-economic development of any society. Energy production is therefore a key challenge for the years to come. It is becoming increasingly problematic with the scarcity of fossil fuel resources on the one hand and the environmental consequences induced by their use on the other (Pujol, 2013).

Its relative importance increases with technical progress, industrialization and the need for modern comfort (Romain, 2014). Improving energy supply and access requires: (i) increasing the share of renewable energies in the energy mix; (ii) facilitating access to modern energy services, (iii) promoting energy empowerment at the national level; (iv) creating energy services, (v) promoting energy efficiency, hence the importance of photovoltaic energy production with higher efficiency (ATEK, 2013). The production of electricity from the sun is based on the physical phenomenon known as the "photovoltaic effect", which mainly consists of transforming the light emitted by the sun into electrical energy through semiconductor devices known as photovoltaic cells. This production varies proportionally with the light shining on the solar module.

A totally cloudy day inhibits the direct component of solar radiation. Module efficiency decreases proportionally cloud density and coverage. The main aim of this study is to quantify the influence of cloud cover on the performance of photovoltaic systems. Clouds cover an average of 68% of the Earth's surface and play a critical role in the Earth's radiation balance (Miguel, 2021).

As they pass over, they can cast partial or total shadows on PV cells. They scatter solar radiation and generate extraordinary optical phenomena. If the module is disproportionately exposed to the sun's rays, the following consequences occur: (i) either the Isc of the shaded cell is greater than that of the unshaded diodes, and in this case, the power delivered by the module is imposed by the lower-powered cell (Thomas, 2014); (ii) or if the Isc of the shaded cell is less than that of the unshaded diodes, then the shaded cell will become a receiver and will have to dissipate the energy supplied by the other unshaded cells. This not only distorts the module's characteristic curve, but also causes the receiver cell to heat up (the "hot spot phenomenon). This can lead to the destruction of the module (Thomas, 2014).

Studies have indicated that the intensity of the drop in energy production from PV fields due to cloudbursts depends on their peak power.

According to Kankiewicz et al., 2010, the greater the peak power of the array, the lesser the impact of cloud passages. For example, it was observed that during the passage of small clouds, the output of individual solar modules dropped by up to 60%, whereas the entire PV field recorded only a 5% drop in output during the same period (Kankiewicz, 2010). This is due to the transient effect of clouds. This means that losses on other modules are compensated for by modules whose cloud impact is not high enough. The main aim of this study is to quantify the influence of cloud transits on the performance of photovoltaic installations using a calculation code in the Matlab environment. More specifically, the aim is to determine the energy production of a few pilot PV fields of different capacities in cloudy and clear-sky conditions, to model the energy production of PV fields in cloudy and clear-sky conditions using empirical radiation prediction models and the single-diode cell model, and then to compare the different productions during these sunshine periods to highlight the influence of cloudy passages on the energy production of PV plants.

2. Materials and Methods

2.1. Materials

To carry out our study, we used modern equipment and devices to carry out the necessary measurements and tests, as well as software for calculations and the use of their climatic databases. The equipment, devices and software are as follows: i-Photovoltaic solar modules; ii-inverters with displays; iii-electrical multimeters to check the continuity of the installations' wires; and iv-a GPS for geographical coordinates.

2.2. Methods

2.2.1. Presentation of the Study Area

Burkina Faso is a landlocked Sahelian country situated in the loop of the Niger River, with a surface area of 274,200 km2. It is divided into 13 administrative regions and 45 provinces, one of which is Kadiogo, with the city of Ouagadougou as its capital. In 2019, Burkina Faso was home to 20,505,155 people, of whom 68.5% (versus 64.9% in 2018) of households use wood as cooking fuel, 11.2% use coal, and 21% use gas (INSD, 2022). There are two (2) seasons of unequal length: a rainy season lasting 3 to 4 months (June to September) and a dry season lasting 8 to 9 months (October to May). Temperatures generally range from 24°C to 34°C in July. Average annual rainfall ranges from 1,300 mm in the south to less than 400 mm in the north. The city of Ouagadougou, capital of Burkina Faso, is located in the Sahel-Sudanian zone at 12° 20' north latitude and 1° 30' east longitude. Its average altitude is 300 meters. With a population of 2.5 million in 2015, its population rose to 3,030,384 in 2019 (INSD, 2022). In recent years, Burkina Faso has seen an upward trend in economic activity, with average annual growth in Gross Domestic Product (GDP) of 5.6% over the period 2011-2017(INSD, 2022). This situation has led to a sharp increase in demand for energy, particularly electricity. The energy sector is characterized by low coverage of the national power grid (35.58% at December 31, 2017) and a strong predominance of biomass (80% from 2013 to 2018). Burkina Faso's electricity production is heavily thermal (88%), in line with other countries in the sub-region except Ghana (35.3%) (Ministry of Energy, 2019). Thermal generation, which rose from 515.4 GWh in 2011 to 986.7 GWh in 2017, has grown by an average of 8.7% per year since 2011 (Ministry of Energy, 2019). Hydropower's 11.4% share fell from 128 GWh in 2017 to 139 GWh in 2016, a reduction of 8.3% (Ministry of Energy, 2019). Figure 1 shows the study area, which is made up of four measurement sites located in the central region. They are constituted as follows: (i) the Loumbila site (P = 1000 W), (ii) the Ouaga 2000 site (P = 2000 W), (iii) the Sandogo site (P = 8000 W) and (iv) the IRSAT site (P = 40000 W). All these sites are currently in operation, enabling us to obtain in situ results.

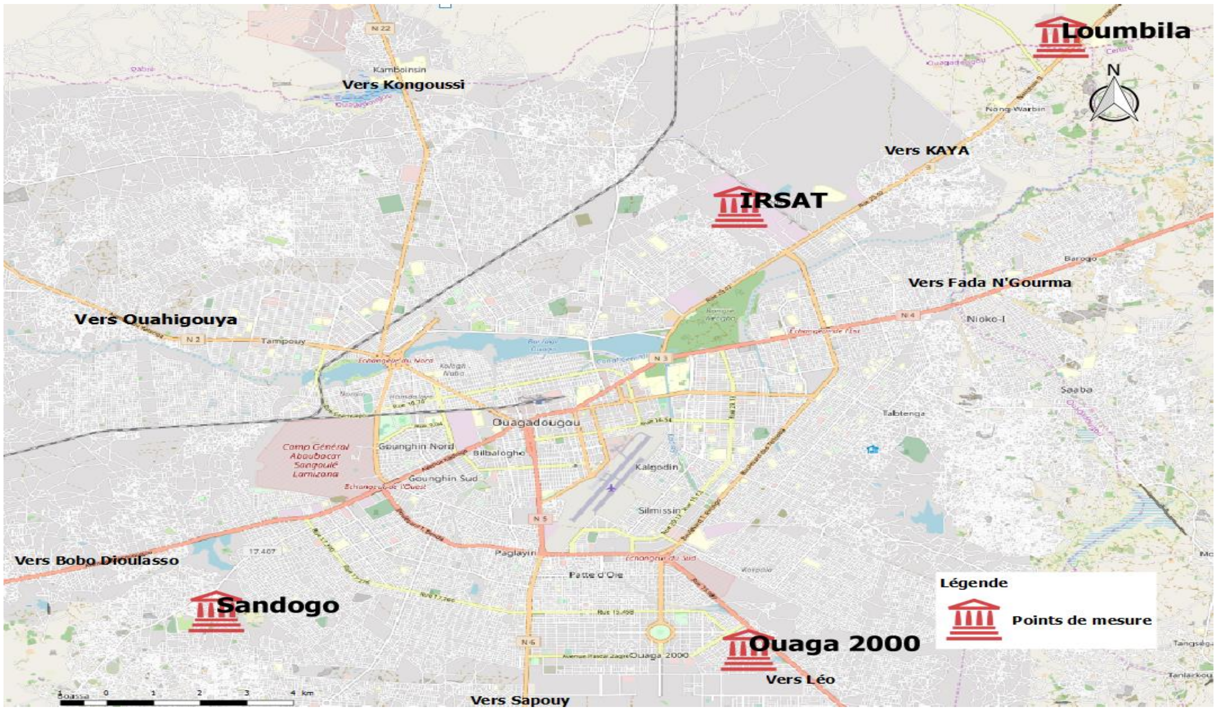


Figure 1 : Overview of study sites

2.2.2. Measuring Conditions

The ambient temperature varies between 16 and 42°C, and the parameters measured are voltage and current. These parameters are supplied by the inverters at the various sites. Geographical coordinates and ambient temperature values were recorded using smartphone applications named Compass for geographical coordinates and Daily Weather for ambient temperatures. Two measurement campaigns were carried out : one during the rainy season (August–September 2019), when the sky is mostly cloudy, and another during the dry season (January 2020), when the sky is clear.

Before starting the measurements, it was necessary to check that the installation of the study site had been carried out correctly. The various sites were installed in compliance with current standards by professional contractors. The check consisted of detecting potential contact faults in the wires, the inclination of the solar modules, and problems of current leakage. Following the preliminary checks, we proceeded to record the site's electrical energy production data. For this purpose, a data sheet was designed, which can be seen in the appendix. From 6 :00 a.m. to 6 :00 p.m., we collected the data supplied by the inverter.

In terms of measurements, for each site, clear and cloudy days were chosen to track production. The numbers of these measurement days are then used to estimate the theoretical production of these sites, enabling a comparison to be made. For the materialization of cloudy passages and its probabilistic character, a random function was used whose value varies from 0 (clear sky) to 1 (cloudy sky).

The collected data was entered into an Excel file, enabling us to perform the various calculations and graphs required for analysis. The characteristics I (V), P (V) and the curve of the power produced throughout the day are produced.

The disparities between these different characteristics, depending on whether the sky is overcast or not, will provide a qualitative and quantitative assessment of the impact of cloudy periods on the output of solar photovoltaic modules. Based on the visualization results, a calculation is made of the differences in parameters (current, voltage and power) between the measurement days.

2.2.3 Modeling the Photovoltaic System

The solar cell model used in the present work is the single-diode model used by Haroon A., Ikhlaq H. 2017 and then by Khanam J., Foo S., 2018. This model is based on an equivalent schematic of a photovoltaic cell consisting of a diode, two resistors and a current generator.

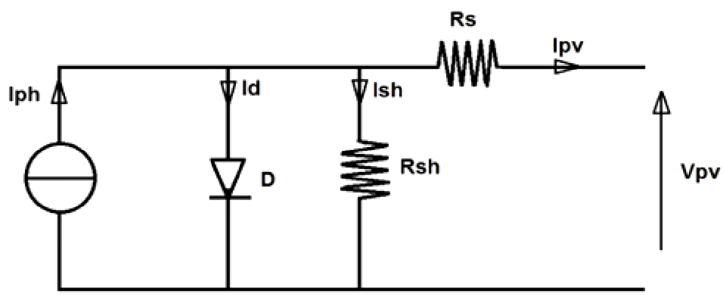


Figure 2 : Electrical model of a PV cell (Haroon et al., 2017)

From the circuit shown in Figure 2 and applying Kirchhoff's theorem, we obtain the following equations:

The photon-current is given by equation (1) :

$$I_{ph} = [I_{sc} + K_i.(T - 298)].\frac{I_r}{1000} \quad (1)$$

The inverse saturation current is given by equation (2):

$$I_{rs} = \frac{I_{sc}}{\left[exp\left(\frac{qV_{oc}}{N_s knT}\right)\right]} \quad (2)$$

The saturation current is given by equation (3):

$$I_0 = I_{rs}.\left[\frac{T}{T_r}\right]^3 .exp\left(\frac{q.E_{go}}{nk}.\left[\frac{1}{T_r} - \frac{1}{T}\right]\right) \quad (3)$$

Module output current is given by equation (4):

$$I_{PV} = N_p.I_{ph} - N_p.I_0.\left[exp\left(\frac{\frac{V_{PV}}{N_s} + I_{PV}.\frac{R_s}{N_p}}{n.V_t}\right) - 1\right] - I_{sh} \quad (4)$$

Where :

$$V_t = \frac{k.T}{q} \quad (5)$$

$$I_{sh} = \frac{V.\frac{N_p}{N_s} + I_{PV}.R_s}{R_{sh}} \quad (6)$$

2.2.4. Modeling Solar Radiation and the Influence of Cloud Cover

The numerical study of solar radiation requires knowledge of a few astronomical and angular formulas.

Hour angle : the sun's hour angle is determined by the earth's diurnal rotation around its axis. This angle is expressed in (°) and is given by the following equation (7) :

$$\omega=15.(TSV-12) \quad (7)$$

Solar declination: the declination of the sun (δ) is the angle between the direction of the sun and the equatorial plane of the earth:

$$\delta=23,45.\sin(360/365.(j+284)) \quad (8)$$

d = day number since January 1st

Sun height and azimuth: height is the angle (h) formed by the horizontal plane at the observation point and the direction of the sun. It is given by the following relationship

$$\sin(h)=(\sin(L).\sin(\delta))+(\cos(L).\cos(\delta).\cos(\omega)) \quad (9)$$

The azimuth is defined by :

$$\sin(\gamma)=(\cos(\delta).\sin(\omega))/(\cos(h)) \quad (10)$$

Latitude (L) : this is the latitude of the location in degrees and angle of inclination β : this is the angle of inclination of the plane in relation to the horizontal in degrees.

2.2.5. Theoretical Determination of Solar Radiation

To determine global solar radiation in the presence of clouds (Gn), we need to know, in addition to the astronomical quantities already calculated, those required to calculate global solar radiation on a horizontal plane and on an inclined plane. The presence or absence of clouds is a key factor in determining the power of solar radiation received on the ground. There are several empirical models for simulating radiation under different atmospheric conditions (Eslemhoum *et al.*, 2019). These include.

Perrin de Brinchambaut's semi-empirical model, which considers global radiation on a horizontal plane to be the sum of direct and diffuse radiation (Capderiou, 1988).

Liu and Jordan's solar radiation model, which considers that global radiation arriving at an inclined surface is the sum of three (03) components : direct, diffuse, isotropic, and diffuse from the sky (Liu and Jordan, 1960),

Capderou's model, which uses an atmospheric haze factor to estimate the direct and diffuse components of illuminance received on an inclined plane. Based on the work of C. Perrin de Brichambaut, Capderou proposes a mathematical model for estimating direct and diffuse radiation incident on a horizontal plane (Yettou, 2009).

The Eufrat model, based on the synthesis of various works, in particular those of Brichambaut, Kasten and Hay, proposes a mathematical expression for calculating the atmospheric mass crossed (Bourges, 1992).

The R.sun model expresses normal direct radiation as a function of a transmission factor T_n (T_{LK}), which gives a theoretical diffuse illuminance on a horizontal surface (Hofierka, 2002 ; Hamani, 2005).

Reindl's model also considers horizon illumination in addition to the diffuse isotropic component and circumpolar radiation, uses a definition of the anisotropy index (Ai) (Farzad, 2012 ; Ana et al., 2013 ; Soteris, 2014).

What all these models have in common is the consideration that overall radiation on a horizontal plane is the sum of direct and diffuse radiation. The Perin de Brinchambaut model will be used for the remainder of this article, due to its simplicity of approach. The state of cloud cover is determined by the daily insolation fraction defined by equation (11) : Fraction of daily insolation :

$$F = \frac{D}{D_0} \qquad (11)$$

Maximum sunshine duration :

$$D_O = \left(\frac{2}{15}\right) * arcos(-tan(L) * \tan(\delta)) \qquad (12)$$

D is the duration of daily insolation and D_0 is the astronomical duration of the day (interval between sunrise and sunset). The parameter F models the state of cloud cover in the sky. It varies from 0 to 1 (0 < F < 1). F=1 characterizes a totally cloudy sky, while F=0 characterizes a clear sky. According to Angstrom's formula, the average global irradiance on an inclined plane for any day with clouds compared to the global irradiance on an inclined plane for a clear day is given by the relationship (13) :

$$G_n = G_i(a.F + b) \qquad (13)$$

Where : $a = 0{,}49$ et $b = 0{,}45$ are constants for all locations, according to the results of A. Mefti and M.Y. Bouroubi, 1999.

$$G_i = (S_h.R_b) + D_h.\left(\frac{1+cos\ (\beta)}{2}\right) + \rho.(S_h.D_h).\left(\frac{1-cos(\beta)}{2}\right) \qquad (14)$$

where :

$$R_b = \frac{cos(L-\beta)cos(\delta)cos(\omega)+sin(L-\beta)sin\ (\delta)}{cos(L)cos(\delta)cos(\omega)+sin(L)sin(\delta)} \qquad (15)$$

β : angle of inclination of the plane to the horizontal ; ρ : ground albedo ; R_b is the inclination factor of direct radiation

Direct irradiation on an inclined plane is expressed by equation (16) :

$$S_i = S_h.R_b \qquad (16)$$

Diffuse irradiation on an inclined plane is given by equation (17) :

$$d_i = d_h\left(\frac{1+cosi}{2}\right) \qquad (17)$$

Reflected irradiance on an inclined plane is given by equation (18) :

$$d_{ri} = (G_h)\left(\frac{1+cosi}{2}\right) \qquad (18)$$

The direct and diffuse components of global solar radiation in a horizontal plane considering the state of the sky (clear or cloudy) according to the Perrin de Brichambeaut model are given by equations (19 to 21) (Capderiou, 1988) :

Diffuse irradiation on a horizontal plane :

$$D_h = B\big(sin\ (h)\big)^{0,4} \qquad (19)$$

Direct irradiation on a horizontal plane :

$$S_h = A.\sin(h)\,.\,exp\left(\frac{-1}{C.sin(h+2)}\right) \quad (20)$$

Global irradiation on a horizontal plane :

$$G_h = S_h + D_h \quad (21)$$

Parameters A, B and C define the aerosol coverage state of the sky. Table 1 shows the sky states considered in the Perrin de Brichambeaut model.

Table 1. Values of coefficients A, B and C (Capderiou, 1988)

Nature of the sky	A	B	C
Very clear skies	1300	87	6
Medium sky	1230	125	5
Polluted skies	1200	187	4

Figure 3 shows the flowchart of the calculation program developed. This flowchart shows the various calculation steps involved in obtaining the power of a PV field under cloudy illumination.

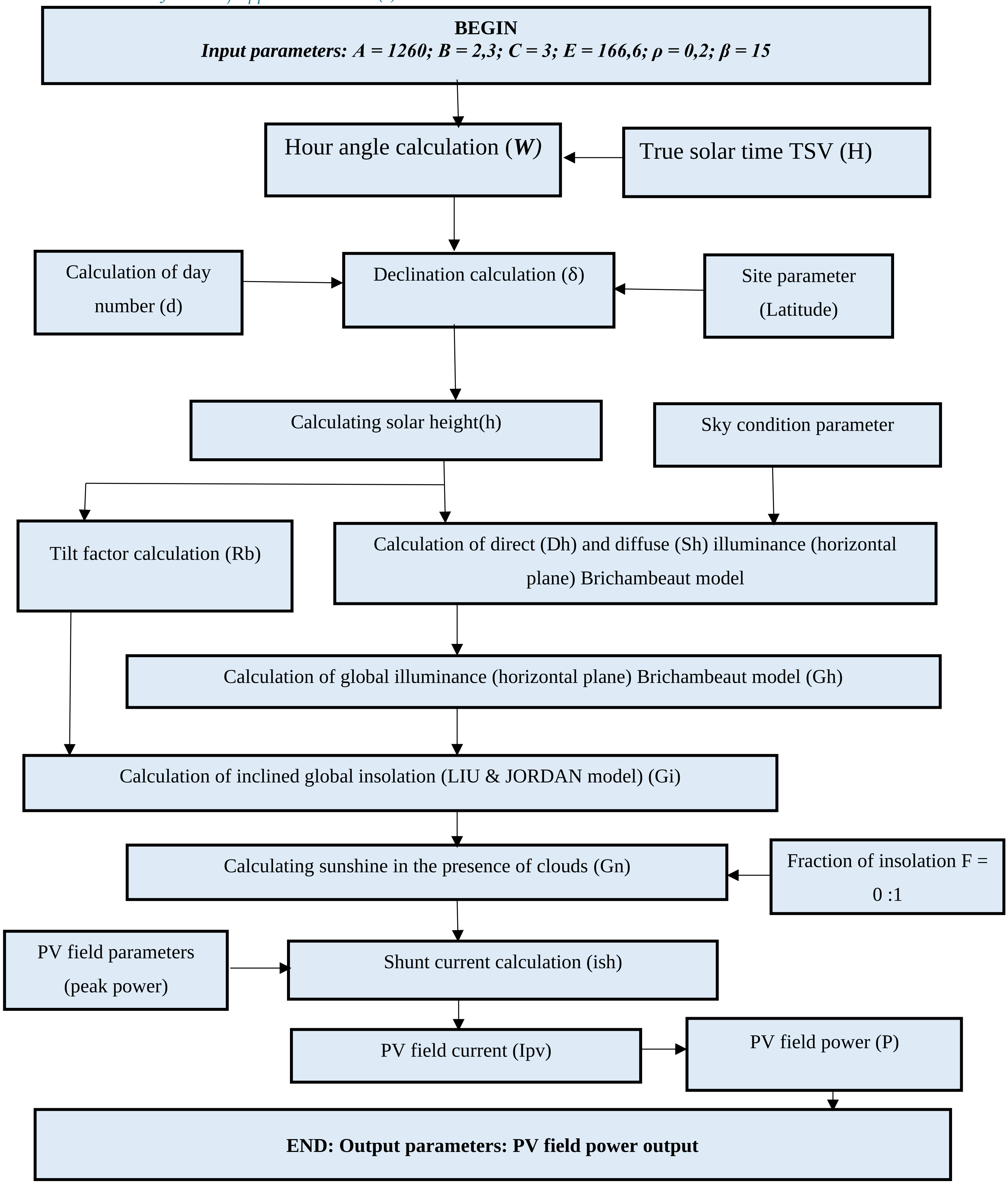


Figure 3 : Algorithm for determining the power of a PV array in cloudy conditions

3. Results and Discussion

3.1. Experimental and Theoretical Electrical Output of the Various PV Fields

Figure 4 shows the simulated and experimental results for the various study sites (Ouaga 2000, Loumbila, Sandogo and IRSAT) under standard conditions as a function of day number and latitude. These curves show the evolution of daily production at each of the study sites, both under standard conditions and under cloudy conditions.

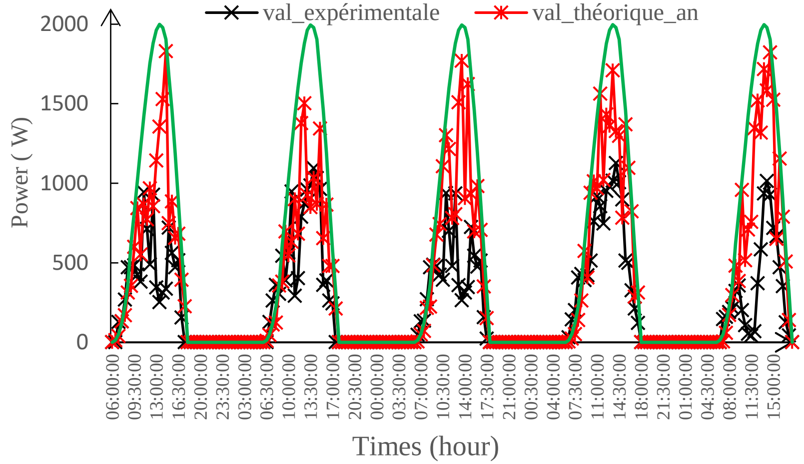
It was noted that the evolution of energy production is similar to that of sunshine. It can be seen that for each site, the theoretical maximum electricity production is obtained around 1 :30 p.m.–2 :00 p.m. This is in line with sunshine trends in the study area. It is also important to note that the curves of maximum theoretical daily production with the presence of clouds obtained are close to the peak powers of the various fields studied. These results indicate that the calculation code used translates reality fairly faithfully. They also show that, in the absence of cloud cover or aerosol pollution, theoretical electrical output is virtually identical for each of the sites studied on the days in question.

From the results obtained, we note that fluctuations in the evolution of modeled and experimental daily power are similar for some sites (Ouaga 2000 ; Loumbila and Sandogo). The discrepancies observed are attributable to the random nature of the definition of cloud cover in the program code. The choice of the factor expressing the instantaneous coverage may not correspond to the actual cloud cover situation, due to the random choice of the F value. At the IRSAT site, the fluctuations are very different in the model and in the experiment. There are several reasons for these discrepancies:

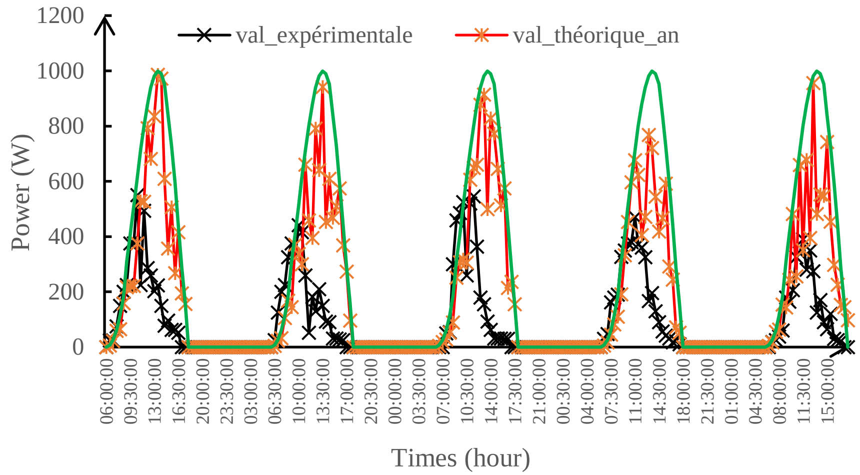
(i) The influence of the deterioration of certain PV field modules. Some modules in IRSAT's PV field have deteriorated, which has a drastic effect on daily production ;

(ii) The influence of shading. The position of the site's PV field is subject to shading from the surrounding trees, which also has a negative influence on the site's production. This shading is probably one of the reasons for the deterioration of certain modules observed with the "hot spot" phenomenon;

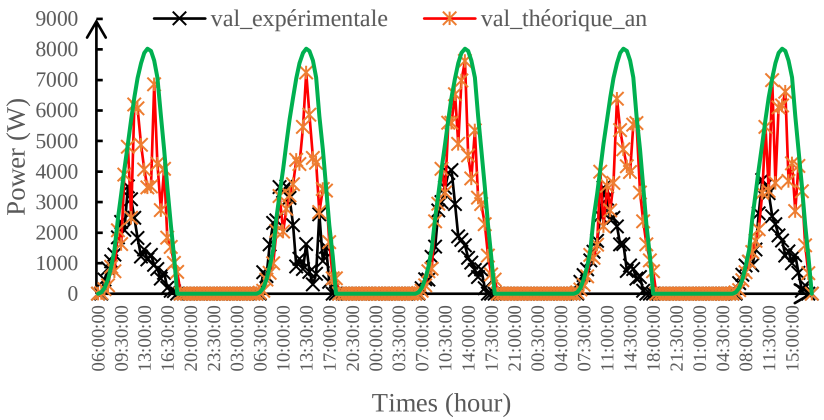
(iii) The influence of dirt (dust deposits). The IRSAT site is located on a major unsealed road with heavy traffic. As a result, the rate of soiling is very high, and as the site does not have a regular cleaning plan, this aspect has a strong impact on the site's production. This aspect is valid for all the sites studied.



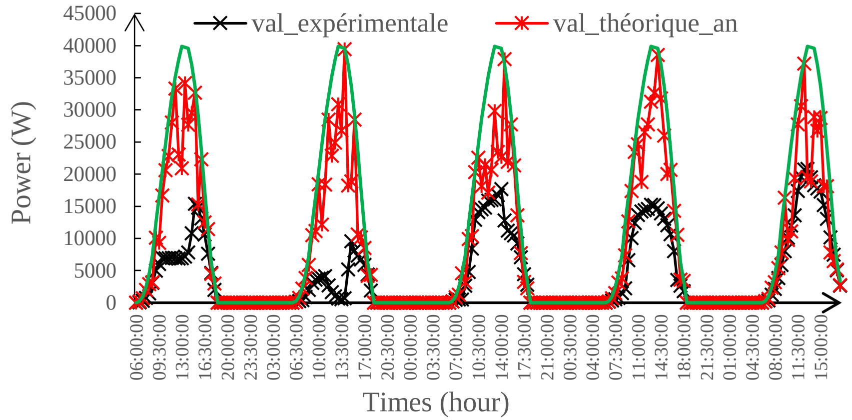
a) Ouaga 2000 site from August 26, 27 and 28, 2019 and September 16, 17,



b) Loumbila site, September 3, 4, 5, 6 and 7, 2019



c) Sandogo site on January 13, 14, 15, 16 and 17, 2019



d) IRSAT site on September 8, 9 and 10 and March 02 and 03

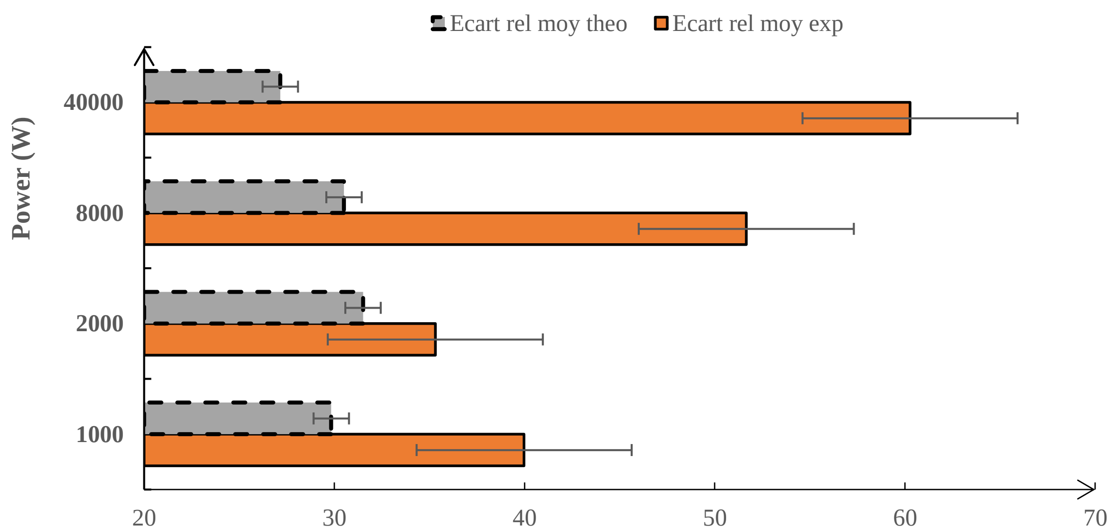
Figure 4 : Theoretical and experimental energy production per day in 2019

3.2 Impacts of Cloudy Periods on PV Module Output as a Function of PV Field Size

Across all the sites studied, it was found that theoretical and experimental electricity production dropped significantly in the presence of clouds. This is because the presence of clouds largely inhibits the direct component of solar radiation, which is the major component of photoconversion on PV cells.

It was also noted that, apart from the Loumbila site (P = 1000 Wp), the impact of cloudy periods was greater for sites with low peak power. This preliminary observation reinforces the results of Kankiewicz et al., 2010, but is not sufficient to confirm their findings that the impact of cloud passages decreases the increase in PV field peak power.

It is important to note that the influence observed is not only attributable to cloud passages, but also to other parameters reported by other authors in similar studies, which were not considered in the present study. These include dust deposition, the obsolescence of some PV cells at certain sites (IRSAT site), and cell temperature. Figure 5 shows the simulated and experimental average losses due to cloud passages as a function of PV field size.



	1000	2000	8000	40000
Ecart rel moy theo	29.84	31.51	30.51	27.16
Ecart rel moy exp	39.98	35.31	51.66	60.27

Loss (%)

Figure 5 : Average power generation losses as a function of PV field size

Average losses were found to vary from 27% to 32% and 35% to 52%, respectively, between simulated and experimental results. These differences can be explained, on the one hand, by the fact that other factors such as temperature and aerosols (dust particles), which have a significant impact on insolation, were not considered, and, on the other hand, by the age of certain PV field plates.

4. Conclusion

The present work consisted of studying the impact of cloud passages on the electrical production of PV fields. Four sites (Loumbila, Sandogo, Ouaga 2000 and IRSAT) were studied using two approaches: (i) an experimental approach in which the production of the various fields mentioned above was monitored online during days with thunderstorm events, and (ii) a numerical approach in which electrical production and the influence of cloud cover on the productivity of the various PV fields were modeled using a numerical code developed under the Matlab environment. The day numbers considered in the experimental approach were used to simulate the production of the various PV fields. In this study, the empirical single-diode model was used to simulate PV module operation under different sunlight conditions (clear and cloudy skies). The main advantage of this model is its simplicity and ease of implementation, based on the technical specifications provided by the manufacturer. Simulation results were compared with data from two sunshine profiles at each of the study sites : (i) a sunny day and (ii) a day with cloudy spells. The following preliminary results were obtained :

(i) Significant discrepancies between measured and simulated experimental data were observed for two sunshine profiles considered. This reflects the difficulty of considering the probabilistic nature of cloud passages and the failure to consider other parameters influencing PV array operation (aerosols, plate temperature and dust deposition) ;

(ii) Theoretical and experimental results indicate that cloud passages have a major impact on the electricity production of photovoltaic systems ;

(iii) The impact of cloudy spells is greater at lower power ratings. This finding corroborates the results of Kankiewicz et al., 2010. However, there is a difference between the theoretical and experimental impact. This is because cloud composition, cloud density and cloud type are not considered.

With a view to improving the results obtained, it is strongly recommended that this work be continued by studying, in addition to cloud passages, the influence of aerosols and dust deposits on PV fields. It will also be more realistic to use other measuring equipment suited to this type of research.

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Credits

Kayaba Haro for investigation, writing - original draft & editing ; Abdoulaye Compaore for investigation and review ; Kabore Abdoulye for investigation and review ; J Ean Gérald Kombassere for investigation and data curation ; Sandwidi Sayouba for paper review ; Tubreoumya Guy Christian for paper review ; Sinon Souleymane for paper review ; Antoine Bere for supervision and methodology validation and paper review ; Oumar Sanogo for supervision and methodology validation and paper review.

Declaration of Competing Interest

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

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