# Contribution to the forecasting and estimation of solar radiation components at ground level in Algeria

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**Abstract:** This paper presents a taxonomy and evaluation of models for forecasting and estimation of various solar irradiation components received at ground; the aim is to compensate for the lack of measures in meteorological stations throughout the country. The chosen models have been proposed in the literature by scientists and researchers. These models are a function of the main meteorological parameters such as relative humidity, temperature, pressure, as well as geographical parameters of the site considered as longitude, latitude and altitude, they also depend to some astronomic parameters like the day number and the solar constant. Three models were studied and simulated for the aim to estimate the solar radiation components at ground level. Finally, comparisons are carried out between the obtained results through simulation and measured values actually found in some Algerian sites where such measurements are possible and available. The aim is to establish the criteria for selecting models according to the geographic and meteorological conditions. The obtained results through simulation of the three models, give good estimate of solar components where errors between the calculated values and those measured are negligible. We can say that the chosen models are good for estimation of solar radiation at ground.

**Keywords:** Solar Radiation, Estimation Models, Solar Components, GISTEL Model, Astronomic Parameters.

## 1. Introduction

The study of solar irradiation at any site is an essential parameter for designers of systems for converting solar energy into electrical energy (photovoltaic modules) or producing hot water (plane concentration collectors). It is used to simulate and optimize the design of systems according to the energy demands to be met. Also, the reconstitution of solar radiation at ground allows designers of solar energy systems to have reliable, precise and easily applicable solar radiation data sequences for the dimensioning of such systems and their installation in any site in the world (Huang et al., 2013; Iqbal, 1980; Moummi et al., 2006; Wu & Chan, 2011).

Algeria is a remarkable country for solar energy exploitation because it possesses a significant solar energy resource, therefore being important to estimate this type of energy for effective sizing in the context of the country's energy transition towards new and renewable energies. In order to know the solar potential in a studied site, there are two sources of solar information; the first is measurable ground data found in solar and meteorological stations, the second involves obtaining solar information from digital satellite photos. In Algeria, only a few sites, nevertheless, took inconsistent measurements of the data related to solar radiation while other meteorological parameters (temperature, humidity etc.) are available and detailed. This leads to use theorical models for estimating of solar radiation at ground, several models have been suggested in previous works (Besharat, et al., 2013; Chen et al., 2019; Khatib et al., 2012). In this study, a few models are described and simulated for estimation of solar radiation based on ground measurements (Hoyt, 1978; Liu & Jordan, 1960; Moummi et al., 2006). A model for processing satellite images (GISTEL model) is also explored (Tadj et al., 2014). The objective of this work is to make a synthesis of the main models applied in the reconstitution of solar ground components and judge the effectiveness and performance of this models, while analyzing the advantages and limits of each of them. These models are based on ground measurements and use mathematical equations to calculate the hourly solar radiation at ground level; they require, on the one hand, the knowledge of meteorological parameters, including humidity $H$, temperature $T$, atmospheric pressure $P$ and, on the other hand, the geographical coordinates of the site under study, such as longitude, latitude and altitude.

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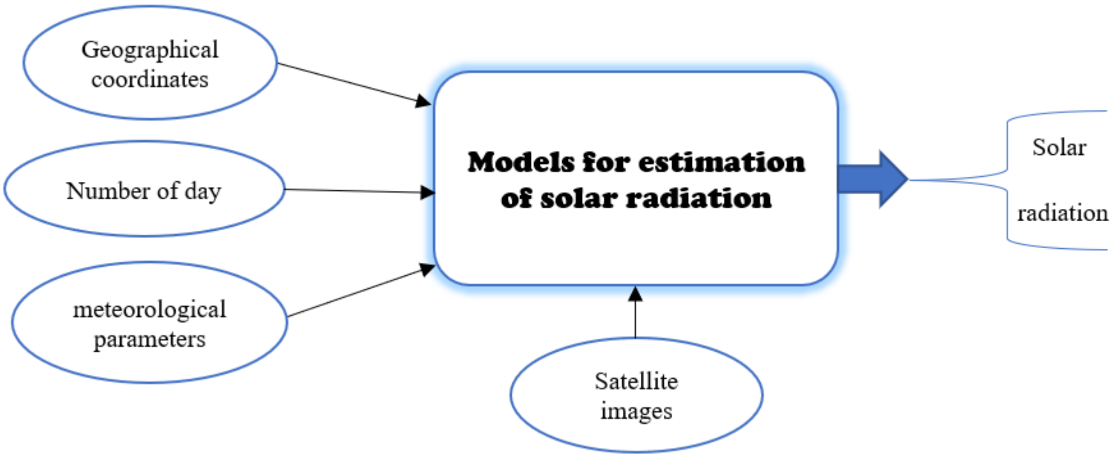



**Figure 1.** Flowchart of the proposed methodology

## 2. State of the art

Previous works will be cited using the models for estimation of solar irradiation. Historically, the first works of modeling of the random variations of the solar radiation using the measured climatological parameters are those realized by Lacis and Hansen (1974), Paltridge and Platt (1976), Davies and Hay (1978), Hoyt (1978), Bird and Hulstrom (1981), Brichambaut (1975) taken over by Capderou (1987) adopted in Algeria. These models have given good results for estimation of solar radiation at ground, but they have two major drawbacks: the first is that they are only valid for a clear sky state, the second is that they need measured data at ground such as relative humidity and temperature, these parameters being not always available.

Liu and Jordan (El Mghouchi et al., 2015; Mefti & Bouroubi, 1999) proposed a simple model which uses as input the number of days of the year, the latitude of the place, as well as coefficients characterizing the sky nature. This model has the advantage over the others that it is independent of meteorological parameters such as temperature and humidity, in addition it is also valid whatever the nature of the sky (clear, cloudy, etc.), but the major drawback of this model is that it considerably overestimates the values of solar components.

After the launch of the first European geostationary meteorological satellite (METEOSAT, GOESSAT etc.), the approach based on satellite images was born. GISTEL model: Solar Radiation by Tele-detection (Gisement Solaire par Télé-détection) is one of the simplified models that have emerged since the gases in the atmosphere contributed to the measurement of radiation. It was initially applied in France on images collected by the METEOSAT2 satellite (Delorme et al., 1992). This model was also validated in Tunisia after the good results obtained by considering various meteorological stations and applying it to B2 images (Ben Djemaa & Delorme, 1992; Chaabane & Ben Djemaa, 2002). Subsequently, it was applied in Algeria with a sequence of 9 images per day during the period of 1994/1995, on METEOSAT type B2 images (Mefti et al., 2008). This model remains a simple method that can give satisfactory results (Tadj et al., 2014).

## 3. Methodology

The work in this article is structured as follows: the first part describes briefly some basic notions on the solar radiation, especially in Algeria. In the second part, different models for estimating of solar radiation at ground will be presented. After, MATLAB environment is used to simulate the proposed models. Finally, the obtained results of the simulation are compared to the actual measured values available in meteorological stations, and the obtained results will be commented and discussed for the aim of verifying and confirming the effectiveness of these models.

# 4. Solar radiation

## 4.1. The solar constant

The solar constant is the intensity of solar energy falling on a surface perpendicular to the sun's rays at the limit of the atmosphere (outside the atmosphere) and at a well-defined distance between the sun and the earth. The value of the solar constant is calculated by the equation (1) (Duffie & Beckman, 2013; Iqbal, 1983):

$$I_{sc} = I_0 \cdot cor \quad (1)$$

$I_0$ : is the solar constant at an average distance of $150.10^6$ km between Earth and Sun, with a value of 1367 W/m$^2$ (Koupelis, 2010; Miller et al., 2010).
$cor$ : is the distance correction factor between Sun and Earth:

$$cor = \left(1 + 0.033\cos\left(\frac{360}{365}(d_n - 3)\right)^{\circ}\right) \quad (2)$$

$d_n$ : is the day number of year, it varies from 1 (January 1) to 365 (December 31).

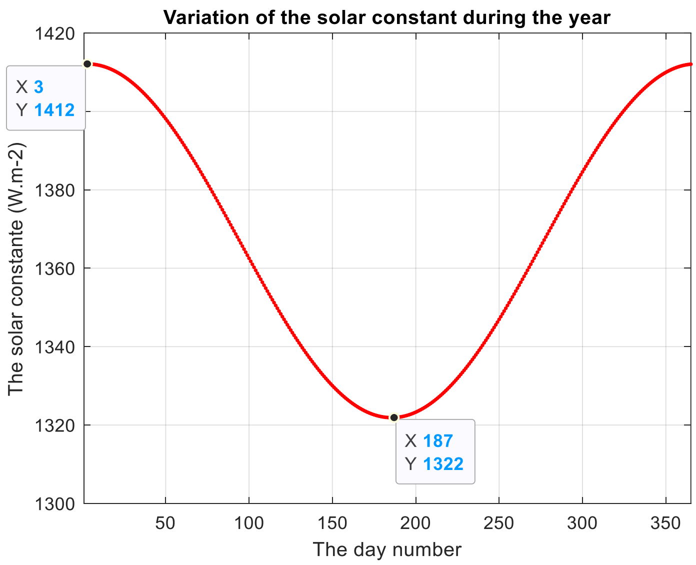



**Figure 2.** Annual evolution of the solar constant

According to Figure 2, it is noticeable that the maximum value of solar constant is obtained in January with the value of 1412 W/m$^2$ and the minimum at the beginning of July, with a value of 1322 W/m$^2$, this being explained by the effect of the variation of the distance between the Earth and the Sun, which is minimal in winter and maximal in summer.

## 4.2. Solar radiation components at ground level

Before reaching ground level, solar radiation undergoes physical variations as it passes through the atmosphere, interacting with the solid and gaseous constituents of the atmospheric layer. This interaction results in the appearance of absorption bands which are added to the spectrum of solar radiation and in an attenuation caused by atmospheric scattering (diffusion). The resulting modification of the spectrum is the result of the process of absorption of ozone, water vapor and other gases such as oxygen, carbon dioxide and methane, on one hand, and diffusion of air molecules, aerosols and clouds, on the other hand (Mefti, 2007).

The solar radiation arriving at ground has three main components: a direct component $(I)$ which reaches the ground unhindered in direct line from the sun, a diffuse component $(D)$ which is scattered by different atmospheric constituents, such as aerosols, dust and clouds, and a reflected component $(R)$ reflected by the ground surface, the whole forming the global radiation $(G)$.

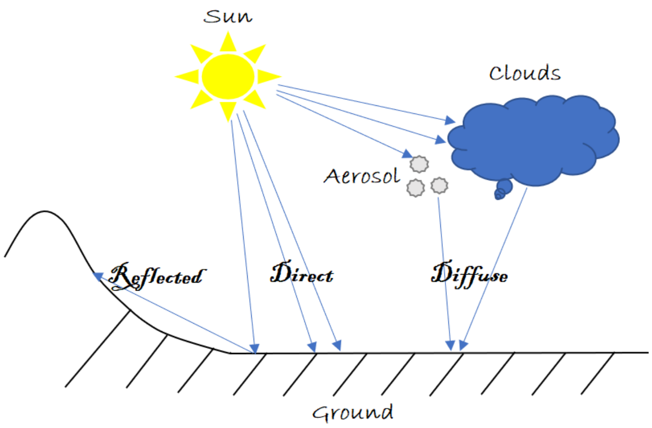
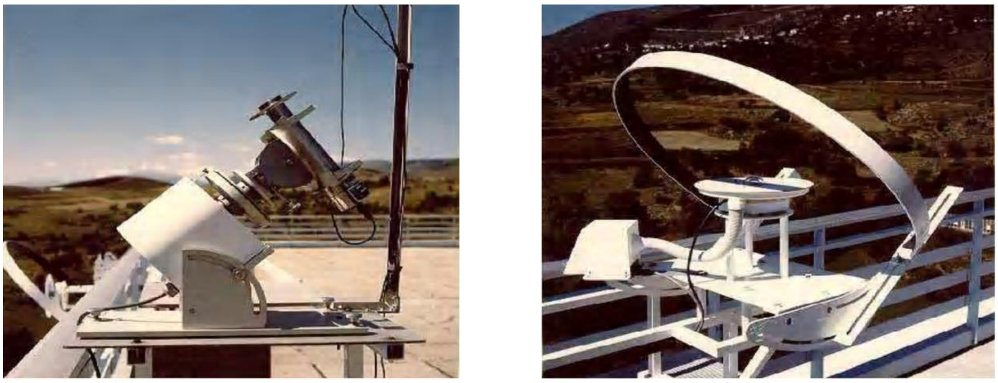



**Figure 3.** Solar radiation components at ground level

## 4.3. Instruments of solar radiation measurements

The general principle of devices for measuring solar radiation at ground level is the transformation of the solar irradiance into heat. The direct component is measured by the pyrheliometer (Figure 4.a), while the global and diffuse components are measured by the pyranometer (Figure 4.b), the measurement of the sunshine duration being made by the heliograph.



(a) (b)

**Figure 4.** Instruments for measuring the solar radiation (a): pyrheliometer; (b): pyranometer

## 4.4. Meteorological stations and solar radiation in Algeria

Algeria is a country with a total size of 2,381,741 km$^2$ and is located in Northern Africa, along the Mediterranean coast. Geographically, Algeria is split into three primary areas that mainly run East to West. The Tell, a Mediterranean coastal location, comes first. The third zone, the Sahara, makes up about 80% of Algeria's land and the second region, the high plateaus, is in the interior of country and is characterized by a varied terrain and cold weather.

Due to its geographical location, Algeria has one of the highest solar radiations in the world. As shown in Figure 5 (SolarGis, 2018), the average annual sunshine is about 2500 hours/year in the North and 3600 hours/year in the South of the country, the daily solar irradiance receiving on a horizontal surface of 1m$^2$ is about of 5.5 kWh on a large part of the country, i.e., nearly 1600 kWh/m$^2$/year in the coastal regions, 1800 kWh/m$^2$/year in the High Plateaus and 2200 kWh/m$^2$/year in the south of the country. However, Algeria has 56 meteorological stations, this number being low compared to the total area of the country, most of these stations being concentrated in the coastal cities and the High Plateaus. However, the number of stations is low in the South, where the solar radiation values are high.

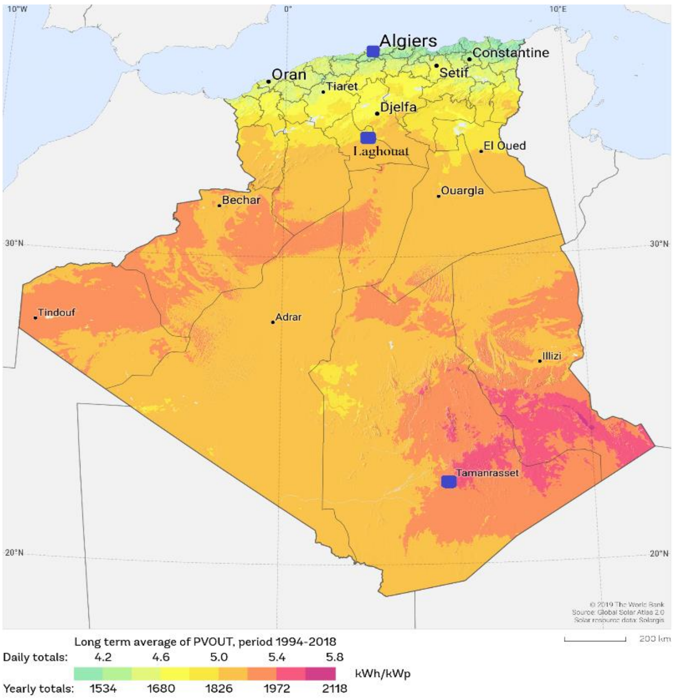



**Figure 5.** Daily and annual solar radiation data in Algeria (SolarGis, 2018)

## 5. Models for estimation of solar radiation at ground

In the following several solar radiation estimation models will be described and classified based on ground data (temperature, humidity, pressure...). It's about of Hoyt model, Liu & Jordan model and a satellite image processing model represented by GISTEL model which estimate hourly solar radiation components at ground.

### 5.1. Model of Hoyt

Hoyt proposed a model to calculate the direct, diffuse and global components of solar radiation (Bird & Hulstrom, 1981; Hoyt, 1978; Rougab, 2011). The global solar radiation given by this model considers the phenomena of absorption and diffusion of solar irradiation by atmospheric components (water vapor, aerosols, ozone, etc.). In this model, the direct radiation on a horizontal plane is given by the relation:

$$I = I_{sc} \cdot \tau_r \cdot \tau_{as} \left( 1 - \sum_{i=1}^{4} a_i \right) \sin(h) \tag{3}$$

$h$: is the solar elevation, defined by the angle between the solar radiation direction and the horizontal plane, its value is equal to zero at sunrise and sunset, it is maximum at noon; the following equation is used to calculate its value (Iqbal, 1983):

$$\sin(h) = \sin(L)\sin(\delta) + \cos(L)\cos(\omega) \tag{4}$$

Where:
$L$ : is latitude of place in degrees.
$\omega$ : is hour angle, it can be defined in degree by (Iqbal, 1983):

$$\omega = 15(12 - TST) \tag{5}$$

$TST$ : is the true solar time (from 1h to 24h).
δ: is the solar declination, it is the angle formed by the Sun direction and the equatorial plane. Its value varies between -23,45° at December 21 (the winter solstice) and 23,45° at June 21 (the summer solstice), it is null at equinoxes (Cooper, 1969). This variation produces the seasons.

$$\delta = 23,45^{\circ} \cdot \sin\left(\frac{360}{365}(d_n + 284)\right)^{\circ} \quad (6)$$

The coefficients $\tau_{as}$ , $\tau_r$ are the aerosols and Rayleigh scattering (diffusion) and $a_i(a_w,a_o,a_{co},a_{ox})$ represent respectively the absorption of water vapor, of ozone, ofcarbon dioxide and of oxygen. These coefficients are a function of temperature and humidity and its values are less than 1.

The diffuse radiation is calculated by the equation:

$$D = I_{sc} \cdot \sin(h) \cdot \left(1 - \sum_{i=1}^{4} a_i\right)\left((1-\tau_r)0.5 + (1-\tau_{as})0.75\right) \quad (7)$$

The reflected component at ground (horizontal plane) is zero, the global solar radiation is the sum of the direct and diffuse components.

$$G = I + D \quad (8)$$

## 5.2. Liu & Jordan model

In 1960, Liu and Jordan devised a simple model that uses the day number of the year, the latitude, and the Sun's elevation to predict the amount of solar radiation components at ground level (Capderou, 1987; Liu & Jordan, 1960; Rougab, 2011; El Mghouchi et al., 2015). The advantage of this model compared to the others is that it makes it possible to generate the solar irradiance received at ground without using meteorological parameters such as humidity and temperature. In this model, the global solar radiation on a horizontal plane (ground) is calculated by the following equation:

$$G = I + D = A \cdot \sin(h) \cdot exp\left(\frac{-1}{C \cdot \sin(h+2)}\right) + B\left(\sin(h)\right)^{0,4} \quad (9)$$

*A*, *B* and *C* depend on the kind of sky, these values as shown in Table 1.

**Table 1.** Values of coefficients A, B and C for the Liu & Jordan model

| Coefficients | Type of sky | | |
|---|---|---|---|
| | Very clear | Medium | Polluted (Cloudy) |
| A | 1300 | 1230 | 1200 |
| B | 87 | 125 | 187 |
| C | 6 | 4 | 2.5 |

## 5.3. GISTEL model

A physical model called GISTEL is used to estimate the hourly solar global radiation for different sky conditions and it is based on satellite images from METEOSAT data. The diagram in Figure 6 summarizes the phases of the selected technique (Tadj et al., 2014).

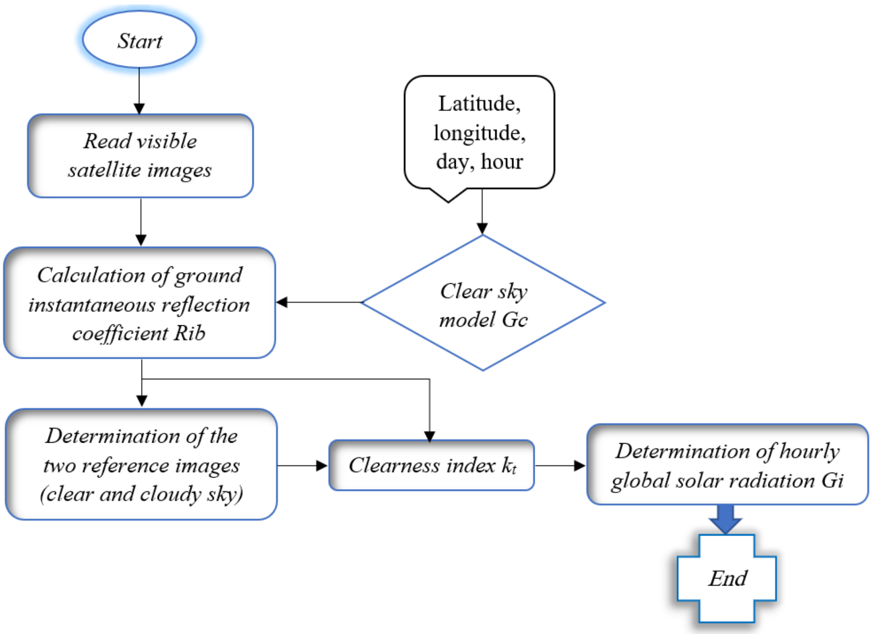



**Figure 6.** Diagram of the GISTEL model

The GISTEL model is based on the following steps:

### 5.3.1. Calculation of the ground reflection coefficients

It is a factor indicating the reflection of solar radiation on the surface. By transforming the brightness of each pixel $Bi(x, y, d_n, h)$ into reflection coefficients $Rib$, this coefficient is a function of the day $d_n$ and the hour $h$ and it is calculated as follows:

$$Rib(x,y,d_n,h) = \frac{Bi(x,y,d_n,h) - Bia(x,y,d_n,h)}{K \cdot G_c(x,y,d_n,h) \cdot T_i(x,y,d_n,h)} \quad (10)$$

Where: $Bia(x,y,d_n,h)$ represents the atmospheric brightness of a clear sky captured on a satellite over the sea and it is constant and equal to 12 (Benmouiza & Cheknane, 2019); $Bi(x,y,d_n,h)$ is the brightness of the *(x;y)* pixel of the visible image; $K$ is the satellite's calibration coefficient and it is equal to 0.514 (Meziani et al., 2013); $T_i(x,y,d_n,h)$ is the reflection factor of the direct radiation component towards the satellite from the ground and it is calculated by:

$$T_i = \left(\frac{1390 - 31 \cdot T_L}{1367}\right) \cdot \exp\left(\frac{-T_L}{12.6\sin(h_\upsilon + 2)}\right) \quad (11)$$

$T_L$: is the turbidity factor of LINKE and varies from 2 for a clear sky to 8 for a humid and polluted sky.

$h_\upsilon$: is the angle height of the satellite:

$$h_\upsilon = Asin\left(\frac{1826\cos(l)\cos(L) - 0.274}{\sqrt{3.41 - \cos(l)\cos(L)}}\right) \quad (12)$$

$l$ and $L$ are respectively the longitude and the latitude of the site.

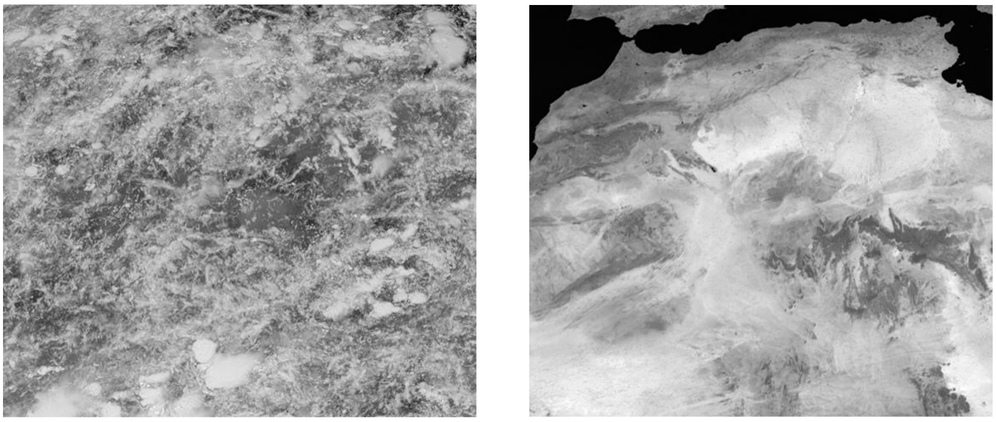
### 5.3.2. Calculation of the hourly global solar radiation under clear sky

The following equation is used to determine the hourly global solar radiation under a clear sky (Benmouiza & Cheknane, 2019; Tadj et al., 2014):

$$G_c = cor \cdot (1300 - 57 \cdot T_L)\left( (\sin(h))^{\left(\frac{36+T_L}{33}\right)} \right) \tag{13}$$

### 5.3.3. Creating of two reference images (clear and cloudy)

To establish the two reference images, series of images taken during a few days at noon for a considerable amount of time are required. The reference images of a clear sky $R_c$ and of a cloudy sky $R_n$ are constructed with the minimum and the maximum values of the reflection factor acquired from these sequences of images.



(a) (b)

**Figure 7.** The two reference images (a): cloudy sky; (b): clear sky

### 5.3.4. Determination of the clearness index

For each image, the reflection coefficients $Rib$ are compared to the clear sky reflection coefficients $R_c$ and the cloudy sky reflection coefficients $R_n$ to determine the clearness index $K_t$. This comparison reveals three different types of skies, including clear sky, slightly cloudy sky and full cloudy sky (Ben Djemaa & Delorme, 1992; Meziani et al., 2013).

$$\begin{cases} \textit{Clear sky} & Rib \le R_c : & K_t = 1 \\ \textit{Slightly cloudy sky} & R_c < Rib < R_n : & K_t = 1 - (1 - K_0)\left(\frac{Rib - R_c}{R_n - R_c}\right) \\ \textit{Full cloudy sky} & Rib \ge R_n : & K_t = K_0 \end{cases} \tag{14}$$

Where: $K_0 = 0.2$ represents the cloudy sky index.

### 5.3.5. Calculation of the global solar radiation

The hourly global solar irradiation for each pixel is obtained by the following equation (Benmouiza & Cheknane, 2019; Mefti et al., 2008; Tadj et al., 2014):

$$G_h(x, y, d_n, h) = K_t \cdot G_c(x, y, d_n, h) \tag{15}$$

## 6. Simulation results and discussion

### 6.1. Data collection

In this study, the data acquired by the ONM (National Office of Meteorology) is used, which provides climatological data (such as humidity, temperature, etc.) and hourly solar radiation for three sites in Algeria: ALGIERS (36.80° N, 3° E, 258 m) which represents the coastal zone, LAGHOUAT (33.80° N, 2.87° E, 760 m) as an internal city of the country and the city of TAMANRASSET (22.78° N, 5.52° E, 1400 m) representing the greater Sahara in South of the country (Figure 5). The data collected covers the period of the year 2021, one day in winter (January 10) and another day in summer (July 17) being chosen for each city in order to validate the accuracy and efficiency of the studied models. In addition, the visible satellite images necessary to GISTEL model are collected from the European Organization for the Exploration of Meteorological Satellites (EUMETSAT) as shown in Figure 7, which illustrates Algeria's satellite image.

## 6.2. Comparison with measured data

To evaluate the performances of the proposed models, the simulation results will be compared with hourly measured data by the calculation of the MAPE (Mean Absolute Percentage Error) between estimated and measured values; this is given by the equation (16) (El Mghouchi et al., 2015). The most effective model is the one with the lowest MAPE.

$$MAPE(\%) = \frac{1}{n}\left(\sum_{i=1}^{n}\left|\frac{G_{est}(i) - G_{meas}(i)}{G_{meas}(i)}\right|\right)\cdot 100; \quad n = 24 \tag{16}$$

The performance of the models is defined according to the values of MAPE as follows:

$$\begin{cases} Excellent & if \quad MAPE \leq 10\,\% \\ Good & if \quad 10\% < MAPE < 20\% \\ Fair & if \quad 20\% < MAPE < 30\% \\ Poor & if \quad MAPE \geq 30\% \end{cases} \tag{17}$$

Figures (8-10) show a comparison between global solar radiation estimated by different models with the experimental data for three locations which have been chosen in Algeria.

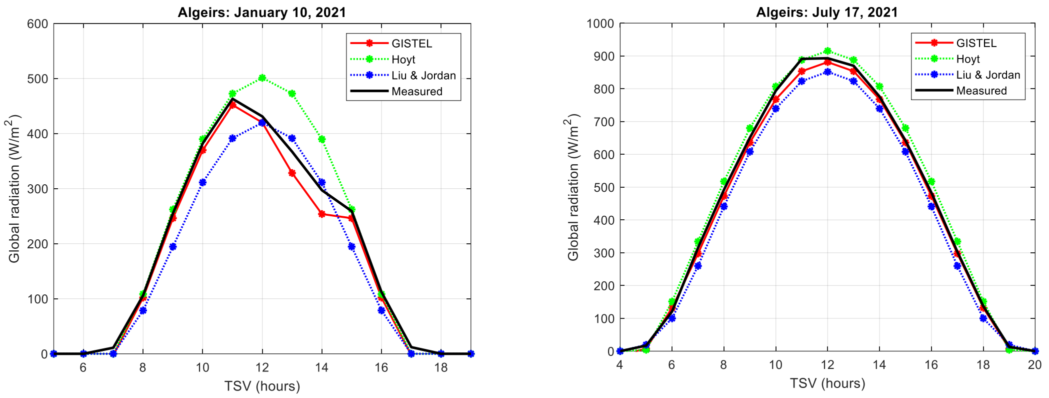



**Figure 8.** Measured and estimated global solar radiation in Algiers

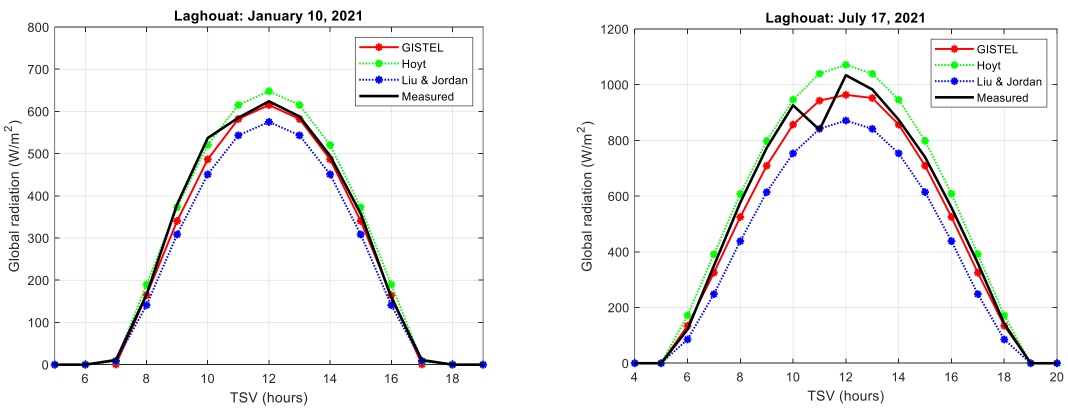



**Figure 9.** Measured and estimated global solar radiation in Laghouat

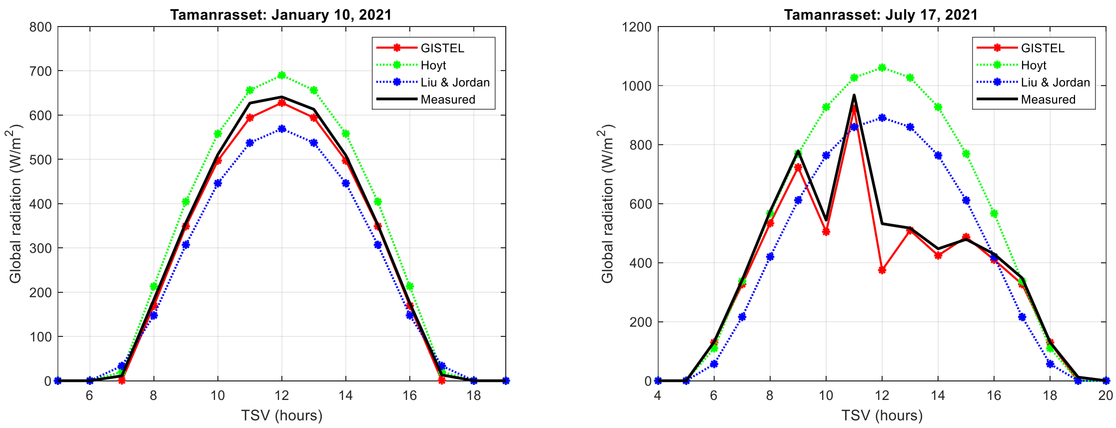



**Figure 10.** Measured and estimated global solar radiation in Tamanrasset

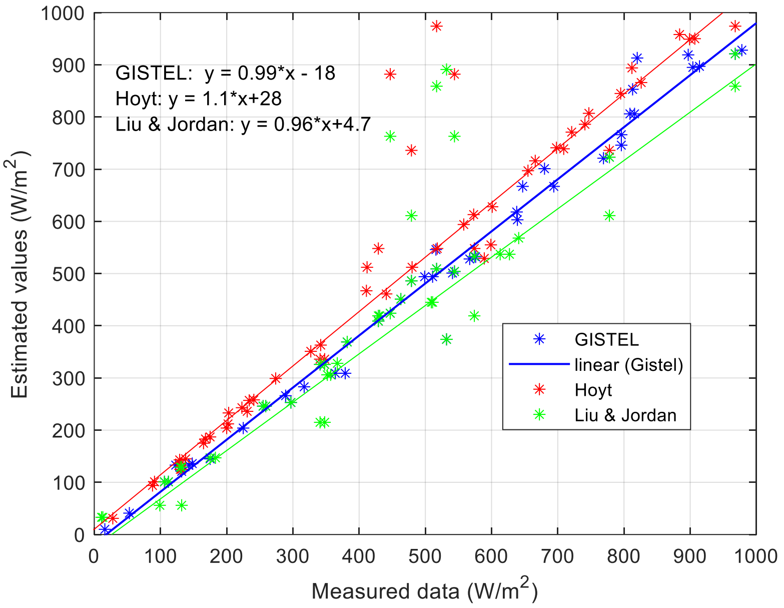



**Figure 11.** Scatter plot between measured data and estimated values by the three models

## 6.3. Analysis of results

As seen in Figures 8, 9 and 10, sometimes the models underestimate and sometimes they overestimate the values measured for the three chosen sites. The difference between the measured values and those calculated is a smaller for the Hoyt model and negligible for the GISTEL model, while it is quite large for the Liu & Jordan model. Indeed, the global radiation is more sensitive to the state of the sky, for which the GISTEL model uses the atmospheric factor of LINKE and for which the model of Liu & Jordan uses constants characterizing of the state of the sky.

For the day of January 10 in Algiers, the GISTEL model follows the measured values, the difference between the measured values and those estimated being very small. In the authors view, the drop in global radiation between 11 a.m. and 1 p.m. could be influenced by climatic variations such as the presence of very frequent clouds in this region during the winter season. On the other hand, Jordan's model significantly underestimates the measured values, the difference between the values of the two curves being clear and possibly exceeding 60 Watts at 11:00. In other cases, the GISTEL model remains the most accurate compared to the Hoyt model which overestimates and the Liu & Jordan model which underestimates the measured values. It should also be noted that in some cases the curves of the values measured are in good agreement with those of the values estimated for the three models, this appearing during the day of July 17 in Algiers and in January 17 in Tamanrasset.

A very important advantage is noticed in the GISTEL model and it follows the climatic disturbances during the day (presentation of clouds, sandstorm, ...), which appears clear for the day of July 17 in Tamanrasset, between 10 a.m. and 1 p.m., unlike other models. It can also be noticed that all the models give good results at sunrise and sunset compared to noon. The estimated values correspond perfectly to the measured data and on the other hand, at noon a difference is noticed especially for the model of Liu & Jordan model and Hoyt model. This can be explained by certain fluctuations that occur at noon due to the presence of clouds and aerosols.

In figure 11, the scatter plot between the measured data and the values estimated by the three simulated models are presented. For the GISTEL model, the relation is a line with a slope almost equal to 1, which confirms the congruence between the measurements and the estimate. The Hoyt model line is above the GISTEL model line, i.e., the estimated values are higher than the measured values. On the other hand, the line of the Liu & Jordan model is below the GISTEL line, which shows that this model underestimates the real values.

**Table 2.** Mean Absolute Percentage Error (MAPE) for three models (%)

| **Model** | **ALGIERS** | | **LAGHOUAT** | | **TAMANRASSET** | |
|---|---|---|---|---|---|---|
| | **January 10** | **July 17** | **January 10** | **July 17** | **January 10** | **July 17** |
| Hoyt | 8.89 | 7.11 | 10.19 | 12.06 | 10.74 | 23.14 |
| Liu & Jordan | 11.53 | 10.37 | 12.32 | 14.59 | 13.68 | 18.07 |
| GISTEL | 5.89 | 4.41 | 6.16 | 7.68 | 6.71 | 5.37 |

Table 2 presents the values of MAPE for the studied models, the GISTEL model having a lowest MAPE (between 4 and 7%). On the other hand, the Jordan model has an acceptable MAPE, which varies between 10 and 20% in most cases, however the Hoyt model has a fairly low MAPE, except for the perturbed day of July 17 in Tamanrasset, which reached 23%.

From the results obtained by simulation and the comparison statistics shown in the Table 3, it can be noticed that the three models remain in good agreement with reality in most days, with an advantage of GISTEL model compared to the other models, so the conclusion is that the GISTEL model leads to better performance, being the most effective model because it has the lowest MAPE, low complexity and a very good precision.

**Table 3.** Comparison between different models

| **Model** | **Input of meteorological parameters** | **Complexity** | **Execution time** | **Precision** | **MAPE** |
|---|---|---|---|---|---|
| Hoyt | Necessary | Medium | Fast | Good | Good |
| Liu & Jordan | Not necessary | Low | Very fast | Medium | Acceptable |
| GISTEL | Not necessary | Medium | Fast | Very good | Excellent |

## 7. Conclusion

The various applications of solar energy systems (photovoltaic and thermal) require a correct determination of the solar energy incident on the studied site. The density of the meteorological network across the country is low. Therefore, theoretical methods are applied for the estimation of incident solar energy at sites where solar radiation measurements does not exist. In this work, two semi-empirical models and one physical model (GISTEL) have been studied and simulated to estimate the hourly global solar radiation and compared with measurements date for three sites in Algeria.

The simulation results demonstrate the effectiveness and performance of the proposed models, as compared to these available with data measured. Each model has advantages and disadvantages, The Hoyt model being a powerful tool for calculating solar radiation, but requiring a lot of data. Liu & Jordan's model is very simple to implement and does not require much computation time, but it significantly underestimates solar radiation values. However, the GISTEL model is in good agreement with reality on most days, the difference between the measured values and those calculated being very small. In addition, this model does not take into consideration meteorological data, only requiring the necessary images to function. In general, it can be said that this model is in good agreement with reality most of the time.

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