Exploring Global Solar Radiation: Enhancing Ground-Level Solar Radiation Prediction using Hottel's Semi-Empirical Model and Sunshine Duration Analysis

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Abstract: - The effective utilization of solar energy at a specific geographical locale is contingent upon the acquisition and assimilation of comprehensive and meticulous solar radiation data pertinent to that specific site. A profound understanding of these datasets constitutes a pivotal factor in the precision-driven design and dimensioning of solar energy systems. It ensues that the attainment of accurate system dimensioning is contingent upon the continual availability of spatially and temporally resolved measurements. The principal objective of this research endeavor is to expound upon the methodological approach employed in the computation of solar energy parameters, alongside the delineation of the pertinent dataset by extrapolating salient insights. Prior to the initiation of any optimization endeavor, a methodical scrutiny of the geospatial and temporal distribution of solar insolation stands as a preeminent prerequisite, indispensably contributing to the efficacious implementation of solar infrastructure. The assessment of solar energy generation potential within the examined region necessitates a meticulous investigation of the theoretical solar resource inherent to Khouribga. Through a meticulous computation regimen encompassing insolation and solar irradiance metrics, this investigation facilitates the discernment of the optimal incident angle for maximal energy absorption by solar photovoltaic cells.

Key-Words: - Solar Energy, Sunshine Duration, Hottel's method, Orientation and Optimum Tilt Angle.

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1 Introduction

Extraterrestrial radiation is affected in various ways during passage through the atmosphere. This section reviews these mechanisms and describes the properties of the solar radiation available at Earth's surface. A short discussion on the radiation and energy balance of Earth is also included.

The efficiency of a solar panel varies with the orientation, inclination, and angle of incidence of the sun's rays. The position you choose for your solar panels will thus influence their production. Different geographical regions experience distinct weather patterns, making the location where we live a significant factor that affects solar system design in several ways. These include determining the orientation of the panels, calculating the number of days of autonomy when sunlight is not available, and selecting the optimal tilt angle for the solar panels [1], [2] & [3].

The previous section allowed us to accurately assess the solar radiation outside the atmosphere, arriving on a surface normal to the incident radiation; but at ground level the radiation received is dependent on multiple constraints:

- Optical: The atmospheric composition layer; humidity, pollution, suspended particles....
- Geometric: Orientation and inclination of the fixed plane collectors.
- Geographical: Latitude, climatic data, configuration, site position...

For solar applications there are several mathematical approaches; which process the solar spectrum received on the ground as a whole; more precisely the power likely to be drawn from a surface with a given orientation (from the south) and of a determined inclination (with respect to the horizontal). Let us quote those which use the various means of investigation and which allow results to be adjusted to reality with an acceptable margin of error.

2 The geometric Position of the Sun (sun Path Diagram)

The apparent movement of the Sun at any given point on Earth is a result of the combined motions of the Earth's rotation on its axis and its revolution around the Sun. From spatial data pertaining to these two celestial bodies, it is possible to ascertain, on one hand, the position of the Sun in the celestial vault based on the site's geographical coordinates (latitude and longitude) and the moment in time (day of the year and hour), and on the other hand, the duration of daylight. The position of the sun is expressed by two angles, namely [4]:

• The angular elevation above the horizon (elevation) commonly referred to as the solar altitude, or alternatively, the zenith angle, which represents the angle between the zenith of the observer's location and the direction of the sun.

• The azimuth, which is its horizontal angle relative to the south (for the northern hemisphere).

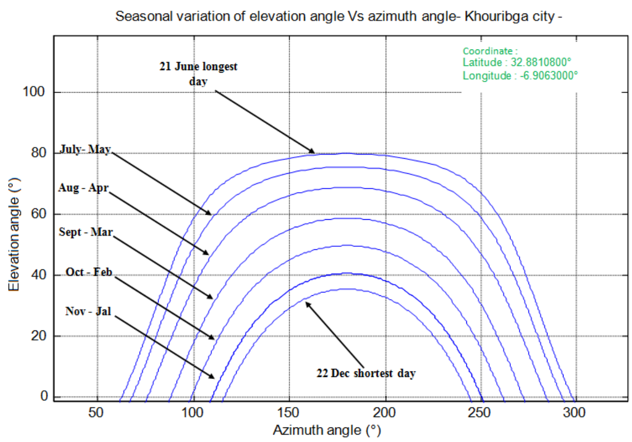

Fig. 1 : Elevation and Azimuth of the Sun throughout the year.

This graph, consequently allows determining the periods of time and days during which the installation will not directly receive the direct solar radiation.

Each geographical point potentially has its own graph of the race of the sun, whose graphs depend on the longitude, latitude and altitude of the place, the graph above presented the race of the sun at Khouribga, with the hours of the day.

The azimuth is the local angle between the direction of due North and that of the perpendicular projection of the Sun down onto the horizon line measured clockwise[5].

0° = due North, 90° = due East, 180° = due South, and 270° = due West.

The following figure represents the solar diagram established in Khouribga city. The sun is located according to the date and time considered [6]:

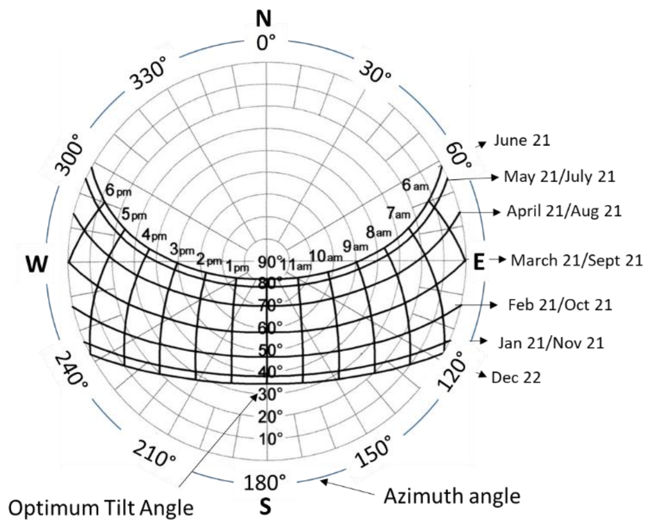

Fig. 2: The solar diagram enables the depiction of the annual path of the sun at (Khouribga, Morocco) over time

We can define the 'astronomical duration of sunlight' or 'day length' as the period of time separating events when the sun is at the horizon. This refers to the sun being at its zenith, where its height is considered zero. Some, like astronomers, take into account refraction, which considers the 'visible' position of the sun. This slightly extends the duration of the day due to the path the ray follows through atmospheric layers of varying optical densities.

3 Sunshine Duration

If we wish to determine how the duration of the day varies throughout the year, the duration appears to be relatively constant around the equinoxes. It is true that the calendar provides us with the sunrise and sunset times. However, using mathematical formulas, more explicit graphs can be drawn, as shown in the figures they follow.

In the first step, we determined the sunrise and sunset times, which means the duration of daylight for given latitudes and longitudes. A solar day is defined as the average time between two successive passages of the sun at the local meridian, and this duration is equal to 24 hours.

3.1 Sunrise and Sunset Time

For observation planning, it is essential to know the times when a celestial body is above the horizon, along with the times of sunrise, sunset, and twilight.

A celestial body can either be continuously above the horizon, continuously below the horizon, or above the horizon for a part of the day, depending on the observer's latitude and the declination of the body [7] & [8].

From the latitude and declination, it is possible to determine the true solar time of sunrise and sunset [9]:

$$\begin{cases} \mathbf{t_{Sunrise}} = -\left(\frac{\text{arcCos}(-\tan(\varphi).\tan(\delta))}{15}\right) \\ \mathbf{t_{sunset}} = +\left(\frac{\text{arcCos}(-\tan(\varphi).\tan(\delta))}{15}\right) \end{cases}$$

However, due to the equation of time, the actual sunrise and sunset times must be shifted by an amount Δt, as defined by the equation:

$$\begin{cases} \mathbf{t_{Sunrise}} = 12 - \left(\frac{\text{arcCos}(-\tan(\varphi).\tan(\delta))}{15}\right) \times \frac{12}{\pi} + \frac{\Delta t}{60} \\ \mathbf{t_{sunset}} = 12 + \left(\frac{\text{arcCos}(-\tan(\varphi).\tan(\delta))}{15}\right) \times \frac{12}{\pi} + \frac{\Delta t}{60} \end{cases}$$

Two corrections had to be introduced to calculate the position of the sun relative to the ideal case of circular motion in the equatorial plane.

3.2 Equation of time

The sum of these two corrections (from the last paragraph of the previous part), it is called the "equation of time," which gives the difference ΔT (in minutes) between mean time and true solar time.

$$\Delta \boldsymbol{T} = (C + R) \times \frac{60}{15}$$

Due to the fact that the Earth's trajectory is an ellipse, consequently, its position is no longer a linear function of the Julian date. It moves faster when it is closer to the Sun than when it is farther away (second law of Kepler or law of areas).

The determination of the equation of time depends on the calculation of two correction factors, denoted as C and R, respectively. We calculate C, and then we need to determine R, which is the correction factor for the declination of the axis of rotation of the earth [10] & [11].

To take into account the ellipticity of the trajectory, we must correct M by a quantity C called the equation of the center, to obtain the true anomaly:

$$\boldsymbol{C} = \eta \sin(M) + 0.02 \times \sin(2M) + \Delta \sin(3M)$$

With : $\eta = 1.9148°$ and $\Delta = 0.0003°$

We call average anomaly (denoted M), the angle covered on this circle by the Earth relative to a reference position. We therefore first calculate the average anomaly M according to the Julian day J (using Julian days allows for a continuous numbering of days, regardless of length of years):

$$\boldsymbol{M} = M_0 + M_1(J - J_{2000})$$

With : $J_{2000} = 2451545$, $M_0 = 357.5291°$ and

$$\boldsymbol{M_1} = 0.9856°/earth\ day.$$

The value of M0 corresponds to the position of the Earth on January 1, 2000, at 12:00 noon (UTC) with respect to the reference position (the perihelion).

$$\boldsymbol{R} = -2.468° \times \sin(2\lambda_s) + 0.053° \times \sin(4\lambda_s) - \xi \times \sin(6\lambda_s)$$

With:

$\xi = 0.0014°$ And $\lambda_s = 280.47° + M_1(J - J_{2000}) + C$

λ_s : is the ecliptic longitude.

UTC : Greenwich Coordinated Universal Time.

The evolution of the equation of time over a complete year is represented by the curve in the figure below:

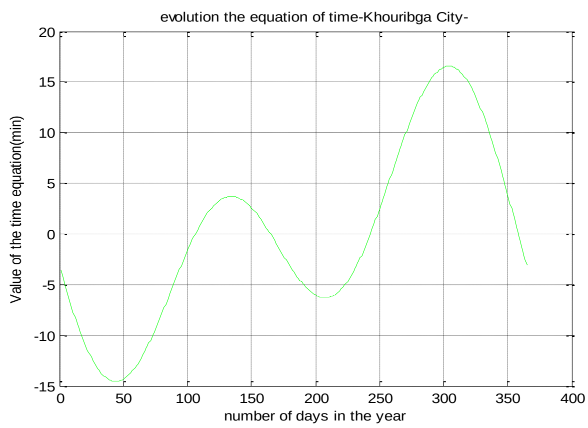

Fig. 3: Equation of time

The equation of time becomes zero four times a year, around April 16th, June 13th, September 2nd, and December 25th. It reached its minimum (-14 minutes 25 seconds) on February 11th and its maximum (16 minutes 14 seconds) on November 3rd [10], [12] & [13].

The shape of the curve representing the 'equation of time,' i.e., the values of the extrema and the moments when they are observed, as well as the instances when the curve crosses zero, evolves very slowly over the years for at least two reasons:

- The Earth in its movement around the Sun is subject to the influence of the other planets of the solar system, resulting in a variation of the eccentricity of its orbit, as well as a slow rotation of the line connecting the perihelion to the aphelion of the orbit, called line of the apses.
- The Earth, in its rotation on itself, undergoes the influence of the couple (Moon, Sun), which involves a variation of its obliquity in inclination and direction.

The seasonal time change aims to shift the sunrise and sunset times by one hour. Contrary to a widespread belief, it has no effect on the duration of the day. It is true that the calendar gives us the times of sunrise and sunset, but by using the formulas, more explicit graphs can be plotted, as shown in the following figure:

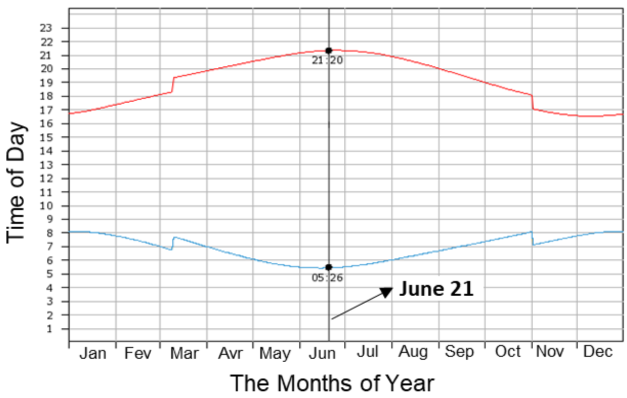

Fig. 4: Time of sunrise and sunset depending on the day

Cette courbe correspondante aux grandeurs sur la ville de Khouribga-Maroc, coordonnées 'Latitude = 33.0295° Nord, Longitude = 7.6197° Est'.

The Daily Sunshine Duration corresponds to the time elapsed between sunrise and sunset. It is calculated using the method described in the following paragraph.

3.3 Daily Sunshine Duration

The effective duration of sunshine or insolation refers to the period of time during which direct solar radiation reaches the ground at a specific location over the course of a day. Direct radiation denotes the solar energy that reaches the Earth's surface without undergoing any deviation from its emission by the Sun.

Another definition of sunshine duration is the length of time that the Earth's surface is irradiated by direct solar radiation, which means sunlight reaching the Earth's surface directly from the sun. Alternatively, it refers to the period during which direct solar irradiance exceeds a threshold value of 120 watts per square meter (W/m2). This value is equivalent to the level of solar irradiance shortly after sunrise or shortly before sunset in cloud-free conditions.

The sunshine duration represents the maximum duration of the day [14] & [15]:

$$\mathbf{Sd} = \mathbf{t_{sunset}} - \mathbf{t_{Sunrise}}$$

$$\mathbf{Sd} = 2 \times \text{arcCos}(-\tan(\varphi) . \tan(\delta)) \times \frac{12}{\pi}$$

We have developed a Matlab code that calculates and plots the daily sunshine duration over the year for the city of Khouribga.

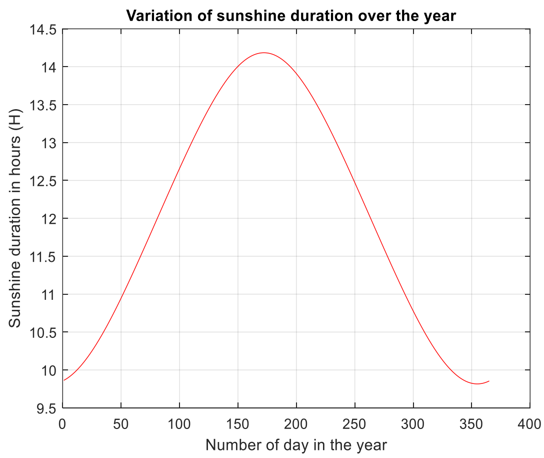

Fig. 5: Variation in Sunshine Duration Throughout the Year of Khouribga city.

The result of this part of the calculation specifies the actual range of daily sunshine time during a year for a geographical area identified by its azimuth, as shown in the figure.

The length of the astronomical day is at its maximum on June 21 (the longest day of the year) and at its minimum on December 21 (the shortest day of the year).

4 Modeling solar radiation at the earth's surface

In accordance with energy requirements, to estimate solar radiation, there are several methods and classical instruments for measuring solar radiation, the most well-known being:

- The pyranometer:It is a device utilized for measuring the global radiation received by a flat surface.
- The heliograph: This instrument measures the duration of daily sunshine.
- Pyrheliometer: It is a radiometer that measures the direct radiation received by a surface normal to the sun's rays.

The objective of this study is not to present these instruments. Therefore, there are other models based on image processing techniques, enabling the estimation of solar radiation flux. The most well-known ones are the physical, analytical, and statistical approaches [16], [17], [18] & [19]. For this purpose, we have selected an approximate model based on Hottel's approach, which provides good results for the estimation of irradiation on a horizontal and inclined plane (an application example in the Khouribga site, Morocco).

4.1 Hottel's method

In a simplified manner, this method read the average value of the power received on the ground, by a horizontal surface, visibility used by meteorologists and coefficients that include atmospheric conditions at the altitude of the site. Obviously, when the capture surface has a given orientation and inclination, to correct this formula by coefficients that take into account the conditions of use [20], [21], [22] & [23].

She utilizes the concept of normalized atmosphere; defined by gas concentrations, the pressure conditions, temperature, humidity, particle concentration, and optical properties.

It should be noted that this method enables interpolation at a given altitude, coefficients within the aforementioned visibility range.

However, the exploitation of these inexhaustible energy resources necessitates the combination of efforts for knowledge and mastery, the creation of accessible databases for exploitation by the various sectors concerned with energy issues. For this purpose, a modular calculation code has been developed in Matlab language, capable of performing the following operations based on the day number and year:

- Determination of the astronomical parameters of the site (rising, setting, declinations, height and angle of incidence).
- Calculation of the inclination factor of the direct radiation denoted by R_b.
- Calculation of direct, diffuse and global radiation on a horizontal and inclined plane.

4.2 Complete model for tilted plane global radiation

To determine the optimal angle of a system, various approaches have been proposed, including comparative statistical studies conducted on different climates, specific regions, or entire continents. Additionally, considerations regarding the nature of the application are taken into account [3] & [24].

4.2.1 First mathematical approach

The global solar radiation incident on the inclined surface of the studied location is estimated using the corresponding components measured for the horizontal surface. The monthly average global solar radiation on an inclined surface (H_{opt}) is the sum of three components: the daily monthly average of diffuse radiation (D_{opt}), the portion of the direct radiation beam (B_{opt}), and the reflected portion (R_{opt}).

The complete model for global radiation in the first mathematical approach on a tilted plane is [25]:

$$H_{opt} = D_{opt} + B_{opt} + R_{opt} = B.R_b + D.R_d + H.\rho.\frac{1}{2}(1 - cos\beta)$$

B is the solar radiation beam, D is the diffuse solar radiation, H is the global solar radiation on a horizontal surface, ρ is the ground reflectivity, and Bi is the sensor tilt angle, Rd is the diffuse radiation conversion factor, and Rb is the ratio of inclined beam radiation to horizontal radiation, and Rb can be calculated as follows:

$$R_b = \frac{\cos(\varphi-\beta)\cos(\delta)\cos(\omega)+(\pi/180)\omega\sin(\varphi-\beta)\sin(\delta)}{\cos(\varphi)\cos(\delta)\cos(\omega_s)+(\pi/180)\omega_s\sin(\varphi)\sin(\delta)}$$

Where δ is the declination angle, φ is the location latitude, and ω is the hour angle of sunrise on an inclined surface, which can be determined as follows:

$$\omega = min\begin{Bmatrix}\omega_s \\ -arcos[\tan(\varphi-\beta)tan\delta]\end{Bmatrix}$$

$$\delta = 23.45sin\left\{\frac{360(n_d + 284)}{365}\right\}$$

We propose - as mentioned earlier - the Hottel method for estimating global solar radiation and diffuse solar radiation on inclined surfaces for the city of Khouribga, which is presented below [26]:

$$R_d = \frac{(3 + \cos 2\beta)}{4}$$

$$\frac{D}{H} = 1.137 + 1.193\left(\frac{S}{S_0}\right) - 1.244$$

Where S represents the monthly average of sunlight during the hour of the day (h), and S_0 represents the daily duration of sunlight during the hour of the day (h). Which can be calculated from:

$$S_0 = \frac{2}{15}cos^{-1}[-tan\varphi tan\delta]$$

4.2.2 Second mathematical approach

The complete model for global radiation in the Second mathematical approach on a tilted plane is is [27] & [28]:

$$I_g = I_{dir} + I_{dif} + I_{gref}$$

With the formula for each component in equations of direct, diffuse and reflected radiation, the complete model is:

$$I_g = I_{dir}.R_b + I_{dir}\left[(1 - A_i)\left(\frac{1 + cos(\alpha)}{2}\right) + A_i.R_b\right] + (I_{dir} + I_{dif}).\rho(\frac{1 - cos(\alpha)}{2})$$

When converting beam radiation between planes we use the geometric factor Rb , which is defined as the ratio of beam radiation on the tilted plane to beam radiation on the horizontal plane:

$$R_b = \frac{I_{dir-T}}{I_{dir}}$$

We can then express I_{dir-T} the beam radiation on the tilted plane as:

$$I_{dir\text{-}T} = R_b.I_{dir}$$

Following the same reasoning as in the figure below, we find that if $I_{dir\text{-}n}$ denotes the beam radiation on a plane perpendicular to the incident radiation, Then:

$$I_{dir\text{-}T} = I_{dir\text{-}n}.\cos(\theta) \quad \text{and} \quad I_{dir} = I_{dir\text{-}n}.\cos(\theta_z)$$

$$R_b = \frac{I_{dir\text{-}n}.cos(\theta)}{I_{dir\text{-}n}.cos(\theta_z)} = \frac{cos(\theta)}{cos(\theta_z)}$$

Where the anisotropy index A_i is defined as the ratio between the incident beam radiation I_{dir} and the extraterrestrial radiation I_0 on the horizontal plane:

$$A_i = \frac{I_{dir}}{I_0}$$

Thus, since I_0 is the incident radiation that would be theoretically possible if there was no atmosphere, A_i is the fraction of radiation that is preserved as beam radiation after it has passed through the atmosphere [29] & [30].

Under clear conditions, I_{dir} approaches I_0 , causing A_i to be close to 1, and the diffuse is treated in the same way as beam radiation:

$$I_{dir\text{-}T} \approx R_b.I_{dir}$$

When there is no beam radiation A_i is zero, and the diffuse radiation is considered purely isotropic:

$$I_{dir\text{-}T} = I_{dir}\frac{(1 + cos(\theta))}{2}$$

Where I_{dir} is modified only by the view factor to the sky.

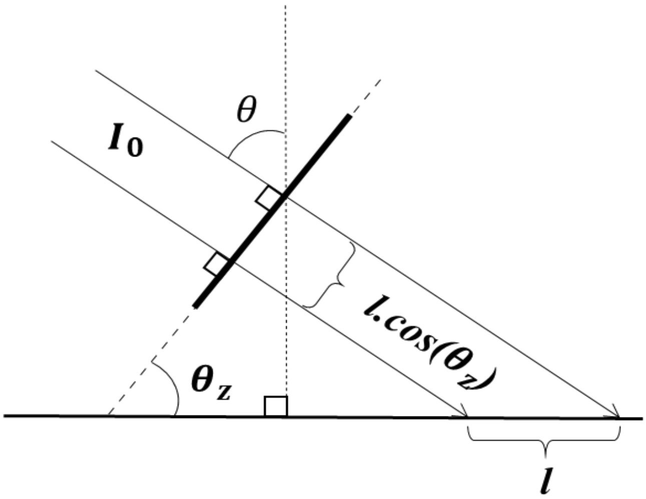

Fig. 6: Conversion between extra-terrestrial radiation with normal incidence and extraterrestrial radiation on the horizontal plane

5 Study of global solar radiation at Khouribga city

The implementation of the mathematical formulas of the previous part gives a clear idea on the different values of daily, monthly and annual energy.

An application developed in Matlab is used in this work to calculate the annual solar energy for a horizontal surface, in the case of Khouribga city is located under 33.0295° as latitude and under -7.6197° as longitude (figure 5).

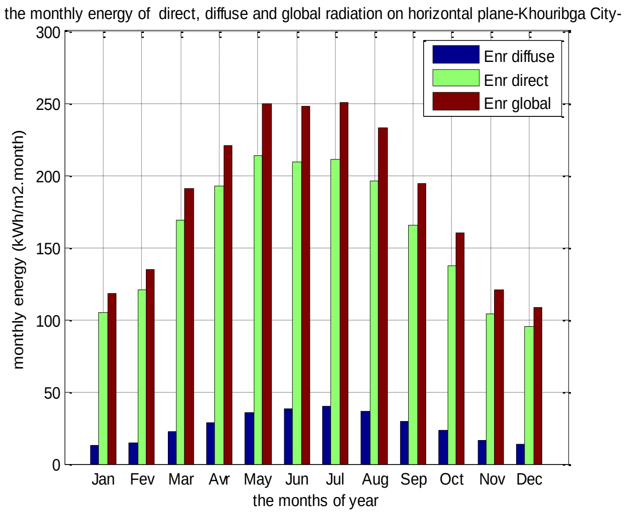

Fig. 7: Distribution of monthly energy in Khouribga city

In the figure representing the energy of solar radiation calculated for the Khouribga site, the summary of the results is given in the table 1.

Through this representation, the annual energy received on a horizontal plane of the Khouribga city is 2241 kWh/m2.

6 Optimum Tilt Angle

The efficiency of a solar module varies depending on the orientation, inclination, and angle of incidence of solar rays. The position that you will give to your solar panels will therefore have an influence on production. The objective of this part is to enable us to determine the optimal position for solar panels in a specific installation.

Taking into account the formulations mentioned above, the energy calculation was developed in MATLAB to determine the annual and monthly energy received. This was accomplished through a simple integral calculation within a regular time interval of 3 minutes. The calculation was applied to a panel surface area of 1 m2, considering inclination angles ranging from 0 to 90 degrees with a 1 degree increment. This allows us to deduce the optimum angle of inclination of the solar panel which would lead to the maximum energy production for a given month and for a year.

Table 1. The monthly and yearly energy received

Months	**The Energy Received per Month (kwh/m^2)**		
	Direct Energy	**Diffuse Energy**	**Total Energy**
Jan	106.68	13.21	119.89
Feb	121.69	14.72	136.41
Mar	170.19	22.12	192.30
Apr	193.15	28.42	221.57
May	214.09	35.75	249.83
Jun	209.47	38.18	247.65
Jul	210.94	39.52	250.46
Aug	196.86	36.05	232.92
Sep	166.37	29.11	195.48
Oct	138.91	23.01	161.99
Nov	106.04	16.33	122.37
Dec	96.79	13.37	110.16
Annual radiation [kWh/m^2.year]	1931	310	2241

The table and the histogram representing the monthly distribution of solar irradiation and for the whole year, informs us about the cumulative energy distribution of the months, we note that the maximum solar radiation greater than 200 kWh/m2 corresponding the summer months (days with high sunstroke), and below 120 kWh/m2 for the winter months, a very remarkable seasonal effect appears on the form of grouping the bars of the histogram.

From the results in Table 2 above, we can plot the annual energy as a function of the angle of inclination (see Figure 8).

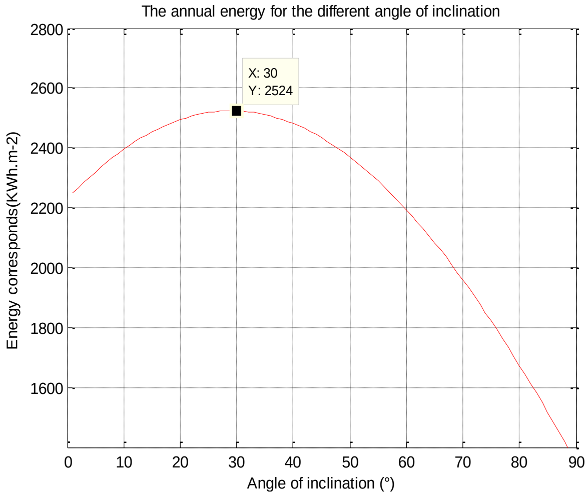

Fig. 8: The annual solar energy for the different tilt angle

From Table 2 and Figure 8, we deduce the optimum angle of inclination (Bopt) for each month and for the whole year. We found that in relation to the site of Khouibga, the optimum angle for the whole year Bopt = 30° and the received energy is E= 2524 kWh/m^2.

fluctuations.

The judicious selection of an apt locale for the deployment of solar modules necessitates the nuanced inclusion of latitude as a pivotal parameter. Notably, this parameter exhibits an escalating salience as the computations unfold, as substantiated by the comprehensive analysis expounded within this discourse.

Within the confines of this scholarly exposition, a comprehensive assessment of the solar radiation potential in the city of Khouriga transpires through the vehicle of theoretical modeling, meticulously delineating the nuances of solar irradiation under clear-sky conditions. It is noteworthy that empirical models proffer themselves as pragmatic tools, adeptly furnishing estimates of diurnal, monthly, and annual mean solar radiation in locales where instrumental measurement resources might be lacking.

Table 2. Energy received each month and per year (kWh/m^2) for different inclination angles varying from 0 to 50 degrees with a step 10 degrees.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual [kWh/m^2]
0°	117.92	134.89	191.06	220.96	249.80	247.93	250.63	232.56	194.41	160.18	120.37	108.05	2228.8
10°	145.40	157.57	209.74	229.69	250.15	244.38	248.92	237.89	208.40	182.28	145.71	135.58	2395.8
20°	168.66	175.68	222.38	231.87	243.50	234.08	240.31	236.56	216.50	199.20	166.86	159.18	2494.8
30°	187.00	188.68	228.22	227.46	230.17	217.56	225.20	228.62	218.46	210.41	183.20	178.15	2523.6
40°	199.86	196.17	228.22	216.60	210.67	195.47	204.36	214.23	214.23	215.58	194.21	191.91	2481.5
50°	206.84	197.93	221.23	199.65	185.68	168.09	178.09	194.27	203.93	214.54	199.54	200.03	2370.4

7 Conclusion

The dynamic interplay of climate change and geographical positioning exerts a profound and discernible impact on the operational dynamics of specific solar technologies. The quantum of electrical or thermal energy harnessed stands inextricably linked to the prevailing meteorological conditions. Consequently, these meteorological parameters manifest as quintessential instruments, wielding paramount significance in the realm of monitoring and gauging the efficacy of diverse solar technologies. Moreover, they furnish indispensable insights for informed decision-making processes concerning the optimal selection of technologies resilient against the perturbations induced by climatic

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