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Article

Extracting the maximum energy from solar panels

Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Nfaoui, Mohamed; El-Hami, Khalil (2018) : Extracting the maximum energy from solar panels, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 4, pp. 536-545, <https://doi.org/10.1016/j.egy.2018.05.002>

This Version is available at:

<https://hdl.handle.net/10419/243537>

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Research paper

Extracting the maximum energy from solar panels

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HIGHLIGHTS

- Using programs through MATLAB to estimate the totality of the solar radiation on any inclined surface, we could determine the optimum tilt angle for daily, monthly and yearly solar radiation relative to the site of Khouribga city in Morocco. The method could be extrapolated to other cities.
- How to extract the appropriate angle under which the maximum energy could be captured and absorbed by the solar cells.

ARTICLE INFO

Article history:

Received 7 July 2017

Received in revised form 12 May 2018

Accepted 15 May 2018

Available online 7 September 2018

Keywords:

Solar radiation

Energy

Inclination

Optimum tilt angle

ABSTRACT

The performance of solar systems to convert solar radiation depends on its inclination angle to the horizontal plane, independently from meteorological conditions. Sunlight should fall with steep angle to extract maximum power from solar panels. Therefore, optimum fixed tilt angles of solar panels should be changed monthly and seasonally. In our study, MATLAB program is used to estimate the total solar radiation on a tilted panel surface with any inclination. The implementation developed to allow us to extract the correct angle at which the maximum energy could be absorbed by the solar cells. We could determine the optimum tilt angle for monthly, seasonal, and yearly solar radiation relative to the site of Khouribga city (latitude 32°52' North and longitude −6°54' West), and we used the same method to draw the table of solar gains depending on the optimum tilt angle of the solar panels to the main Moroccan cities.

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1. Introduction

The design of solar systems requires knowledge of the useful solar radiation received on the surface of the installation, it is one of the essential parameters of the preliminary study. For a given energy need, more energy received means fewer panels to install and vice versa, so in order to study the solar field available on an inclined surface at Khouribga city, a series of insolation and irradiation data compute according to the inclination and orientation of the solar panel, and then we apply the same strategy of this work in 20 Moroccan cities.

In a given city, the annual production of solar energy depends on various factors. Especially:

- Incidental solar radiation at the installation site.
- Tilt and orientation of panels.
- Presence where there is no shading.
- Technical performance of system components (mainly modules and inverters).

In this work, we precede some fundamental notions of astronomy that give information on the radiation received by the ground (diffuse, direct and global).

We have developed a code by using Matlab, and we can give the different coordinate systems used to calculate the solar irradiation, according to time in our city (Khouribga) of latitude 32°52' North and Longitude −6°54' West.

2. Experimental data of solar irradiation in Khouribga city

Currently, in Morocco, measurements of solar radiation data are performed in an instantaneous and continuous manner, this study is carried in the Khouribga city of latitude 32°52.86' North and longitude −6°54.37' West.

This section deals with the daily solar radiation reaching the surface of the earth over a large area, taking full account of seasonal variations in day length, the height of the sun above the horizon, and absorption by clouds and other atmospheric components. Solar radiation includes visible light and ultraviolet radiation.

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Nomenclature

θ	Latitude
α	Tilt angle.
α_{opt}	Optimum tilt angle.
δ	The declination
AH	The hour angle
TSV	The local solar time
H	The elevation
Z	The zenith angle
φ	The Azimuth angle
Z'	This is the angle between the vector normal to the panel and the vertical of the place.
φ'	It is the angle between the projection of the vector to the normal panel on the horizontal plane and the north.
ω	Angle of Incidence
I_0	Extraterrestrial solar radiation (solar constant).
I_{dir}	Direct Irradiation
I_{dif}	Diffused Irradiation
R_{dif}	Correction factor of the diffuse radiation

Daily solar radiation incident on the earth’s surface know the extreme seasonal variation during the year (see Fig. 1).

The most radiant period of the year lasts 3, 6 months, from the first May to 22 August, with incident solar radiation greater than 7.2 kWh/m². The bright day of the year is 21 June, with an average of 8, 3 kWh/m² (Weather Spark, 0000).

The least radiated period of the year lasts 3, 4 months, from 30th October to 10th February, with incident solar radiation below 4,1 kWh/m². The darkest day of the year is 17 December, with an average of 3.0 kWh/m².

The typical day of the month:

For a given magnitude, the typical day is the day of the month approximating the monthly average of that magnitude (Klein, 1977).

The list of the typical days proposed by Klein is shown in Table 1.

We summarize in Table 2, the data of the experimental results of solar irradiation obtained for each typical day in the year (Weather Spark, 0000).

3. Study of global solar radiation at Khouribga city

The study or applications of the solar energy in a given site are depending on more complete and detailed data on the geometric parameters and solar radiation of this site.

3.1. Modeling of geometric parameters – angle of incidence (ω)

The angle of incidence of the solar beam with any surface of inclination and orientation is the angle formed by the direction vector of the solar beam and the normal leaving the surface (Won et al., 1994; Sera et al., 2007) (see Fig. 2).

Where:

h: The angle of the solar height – Elevation

The angle of the sun’s height (h), or the altitude is the angle between the direction of the sun and the horizontal surface; the elevation h from 0° to 90° towards the zenith (Oudrane et al., 2017).

$$\sin(h) = \sin(\theta) \sin(\delta) + \cos(\theta) \cos(\delta) \cos(Ah) \tag{1}$$

Z: The zenith angle

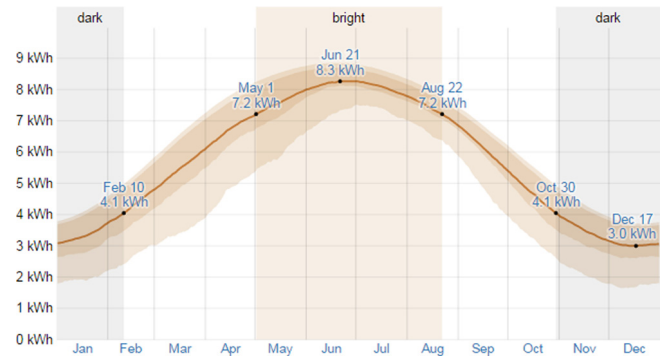


Fig. 1. The daily solar radiation received on a surface of 1 m² at Khouribga city (Weather Spark, 0000).

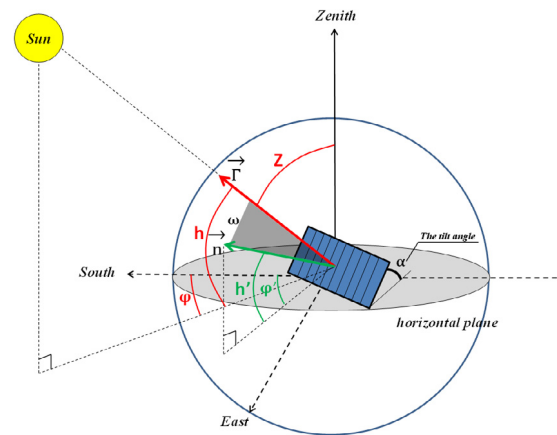


Fig. 2. The solar horizontal coordinates and the angle of incidence.

It is the angle between the direction of the sun and the vertical of the place (zenith). The angle Z is complementary to h (Oudrane et al., 2017).

$$\cos(Z) = \sin(\delta) \cdot \sin(\theta) + \cos(\delta) \cdot \cos(\theta) \cdot \cos(Ah) \tag{2}$$

φ : The Azimuth angle

This is the angle between meridian and the location of the vertical surface passing through the sun (Oudrane et al., 2017).

$$\sin(\varphi) = \frac{\cos(\delta) \cdot \sin(Ah)}{\cos(h)} \tag{3}$$

Every day, the sun describes a trajectory whose two main coordinates, φ and h , are represented on a graph (see Fig. 3).

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 city, with the hours of the day (Ennaoui, 2014).

AH: The hour angle

The hour angle AH is calculated by the daily rotation of the earth around its axis.

$$AH = 15(TSV - 12) \tag{4}$$

TSV is the local solar time.

δ : The Declination

Declination (δ) is the angle between the vector “center of the earth–sun” and the equatorial surface of the earth (Oudrane et al.,

Table 1

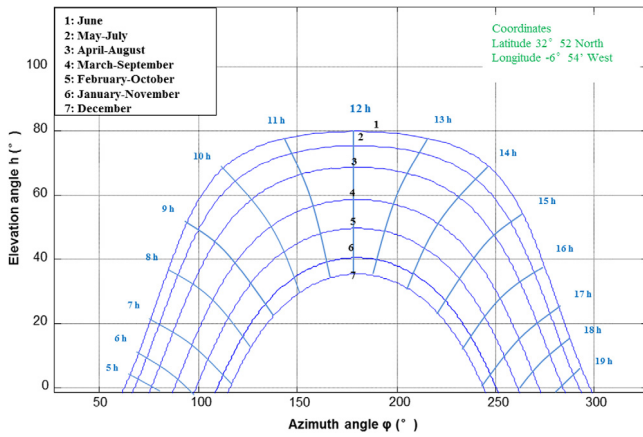
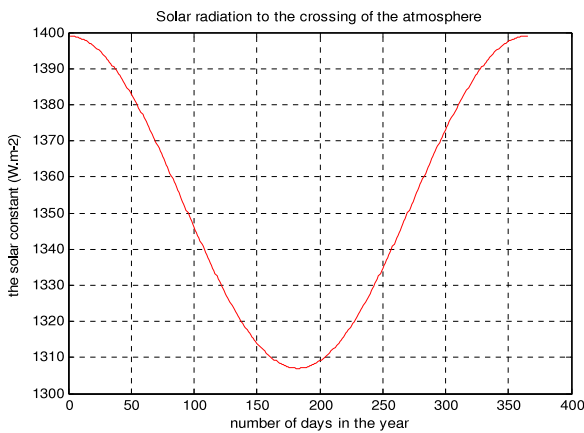
List of typical days per month proposed by Klein.

Month	Jan	Feb	Mar	Apr	may	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Days typical	17	16	16	15	15	11	17	16	15	15	14	10
No. of days	17	47	75	105	135	162	198	228	258	288	318	344

Table 2

Experimental data of solar radiation from Khouribga city.

Month	No. of days	Days typical	Max flux kW/m ²	Energy received kWh/m ²
January	17	17	0,54	3,3
February	47	16	0,66	4,4
March	75	16	0,78	5,4
April	105	15	0,89	6,7
may	135	15	0,94	7,6
June	162	11	0,99	8,2
July	198	17	0,98	8,1
August	228	16	0,95	7,3
September	258	15	0,84	6,2
October	288	15	0,69	5,0
November	318	14	0,57	3,5
December	344	10	0,50	3,1

**Fig. 3.** Diagrams of the azimuth φ and elevation h with the notion of time.**Fig. 4.** Variation of the extraterrestrial solar irradiance.

2017; Crispim et al., 2007).

$$\delta = 23.45 \sin\left[\frac{2\pi}{365}(j + 284)\right]. \quad (5)$$

 j : the sequence number of days in the year. θ : the latitude of the place. \vec{r} : The unit vector carried by the direction of the solar rays. \vec{n} : The unit vector carried by the normal to the surface. ω : **Angle of Incidence** the angle between (\vec{r}, \vec{n}) .

$$\vec{r} = \begin{cases} \sin(Z) \cdot \cos(\varphi) \\ \sin(Z) \cdot \sin(\varphi) \\ \cos(Z) \end{cases} \quad \text{and} \quad \vec{n} = \begin{cases} \cos(Z') \cdot \cos(\varphi') \\ \cos(Z') \cdot \sin(\varphi') \\ \cos(Z') \end{cases}$$

We make the scalar product of two vectors, \vec{r} and \vec{n} for determining the angle ω ;

$$\vec{r} \cdot \vec{n} = \|\vec{r}\| \cdot \|\vec{n}\| \cdot \cos(\omega) = \cos(\omega) \quad (6)$$

$$\vec{r} \cdot \vec{n} = \sin(Z) \sin(Z') \cos(\varphi) \cos(\varphi') + \sin(Z) \cdot \sin(\varphi) \cdot \sin(Z') \cdot \sin(\varphi') + \sin(Z) \cdot \sin(Z').$$

And we have:

$$\sin(\varphi) \sin(\varphi') + \cos(\varphi) \cos(\varphi') = \cos(\varphi - \varphi').$$

We thus find:

$$\cos(\omega) = \cos(h) \cos(\varphi - \varphi') \sin(Z') + \sin(h) \sin(Z'). \quad (7)$$

3.2. Solar radiation to the crossing of the atmosphere

The earth surrounded by its atmosphere intercepts some of the power radiated by the sun; it radiates an approximately constant power. The extraterrestrial irradiance on a surface normal to the solar radiation is given by Won et al. (1994), Ennaoui (2014) and Jan (2011) (see Fig. 4):

$$I_0 = SC \left(1 + 0.034 \cos\left(\frac{360j}{365}\right) \right). \quad (8)$$

3.3. Energy from the Sun at the Earth's Surface

In the previous section, we posed a number of definitions allowing us to formulate the concept of solar radiation outside the atmosphere. This quantity is readily measurable because it is considered that it depends only on the distance between the measuring points of the Sun. We will see in this paragraph, the passage through the atmosphere will tend to complicate the understanding of the

phenomenon, the multiple interactions that may occur, in what follows, we consider the model of inclination of global radiation in the case of a clear sky.

- **Direct-beam radiation:** that passes in a straight line through the atmosphere to the receiver.
- **Diffuse radiation:** that has been scattered by molecules and aerosols in the atmosphere.
- **Reflected radiation:** that has bounced off the ground or other surface in front of the collector.

3.3.1. Direct irradiation

This irradiation is received directly from the sun traveling through the atmosphere without modification. The capture area is placed in the following conditions:

- The sun's position is defined by its elevation (h) and azimuth (φ).
- The azimuth angle (φ) is measured relative to the South.
- The collector plan is oriented with respect to the south and inclined at an angle α as tilt angle.

The received power on the capture area is given by (Ennaoui, 2014; Crispim et al., 2007):

$$I_{Dir} = A \cdot \exp(-K \cdot m). \tag{9}$$

This is an amount that includes the geographic parameters of the system and the astronomical data of the sun in its movement.

$$A = 1160 + 75 \cdot \sin\left(\frac{360}{365}(j - 275)\right) \text{ W/m}^2 \tag{10}$$

$$K = 0.175 + 0.035 \sin\left(\frac{360}{365}(j - 100)\right) \tag{11}$$

$$m = \frac{1}{\sin(h)}. \tag{12}$$

A : apparent extraterrestrial flux.

k : optical depth.

j is the order of the day number in the year, and h is the elevation of the sun.

m is the relative length of the path traveled by the sun's rays through the atmosphere.

The evaluation of the direct energy received in one day on an incline south facing is done by integrating the instantaneous power received.

3.3.2. Diffused irradiation

Clouds, aerosols partly diffuse radiation (Markam and K, 2016; Jan, 2011; Masoum and Sarvi, 2002), as we have previously quantified.

It is assumed that the diffuse flux is uniform in its distribution in the sky which is treated as an infinite surface. This assumption allows us to calculate the correction factor R_{dif} on the diffuse radiation; once the chosen inclination (Sera et al., 2007; Ennaoui, 2014).

$$R_{dif} = \frac{1 + \cos(\alpha)}{2} \tag{13}$$

α is the tilt angle.

The power received on a capture area is:

$$I_{Dif} = C \cdot I_{Dir} \cdot R_{dif} \tag{14}$$

$$C = 0.095 + 0.04 \sin\left(\frac{360}{365}(j - 100)\right). \tag{15}$$

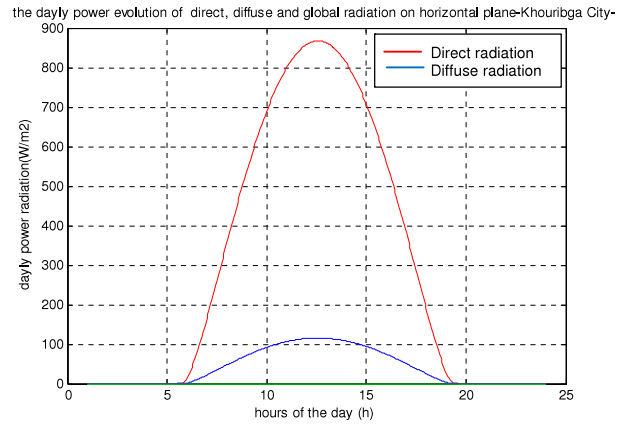


Fig. 5. Both direct and diffuse powers received in function of time.

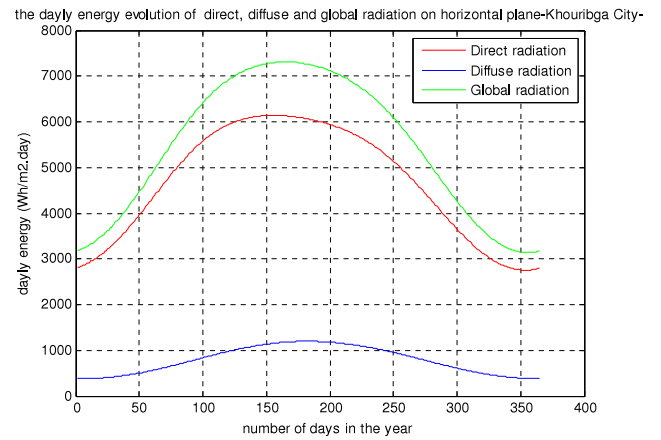


Fig. 6. Annual powers radiations in Khouribga.

R_{dif} is the form factor between collector and sky. The diffused energy received is also calculated in the same way by integrating the power (cf. Fig. 5).

The implementation of this formula gives a clear idea about the different values of energy daily, monthly and yearly.

3.4. Calculation of average distribution of solar irradiation

3.4.1. Calculation of daily irradiation

By using a Matlab code, we can calculate the daily distribution of solar radiation received on a horizontal surface in Khouribga city (the corresponding value of 21 June).

The Matlab code that we have developed, also allows calculating and plotting the daily irradiation of typical days of each month for Khouribga city on a horizontal surface.

The results of daily variations of solar irradiation arriving on a horizontal surface are given in Table 3.

3.4.2. Calculation of monthly irradiation

The graph below shows the evolution of the monthly irradiation on a horizontal surface (see Fig. 6).

The figure shows the values of the daily energies of the solar radiation received on a surface relative of the Khouribga city, according to the days of the year in [kWh/(m² day)].

The curve analysis obtained above indicates that the values of direct, diffuse and global solar radiation are maximum in summer and minimum in winter. The global solar energy has exceeded 7000 Wh/m² for summer days, on the other hand, for winter days to extend between (3000 and 6000 Wh/m²).

Table 3
The energy received per days (Wh/m²).

Month	Days typical	No. of days	Direct energy	Diffuse energy	Total energy
January	17	17	3442	397	3839
February	16	47	4346	526	4872
March	16	75	5490	713	6203
April	15	105	6439	947	7386
may	15	135	6906	1153	8059
June	11	162	6982	1273	8255
July	17	198	6804	1248	8052
August	16	228	6350	1163	7513
September	15	258	5546	970	6516
October	15	288	4481	742	5223
November	14	318	3535	544	4079
December	10	344	3122	431	3553

Table 4
The monthly and yearly energy received.

Months	The energy received per month (kWh/m ²)		
	Direct energy	Diffuse energy	Total energy
January	106,7	13,2	119,9
February	121,7	14,7	136,4
March	170,2	22,1	192,3
April	193,2	28,4	221,6
may	214,1	35,7	249,8
June	209,4	38,2	247,6
July	210,9	39,6	250,5
August	196,9	36,0	232,9
September	166,4	29,1	195,5
October	138,9	23,0	161,9
November	106,1	16,3	122,4
December	96,8	13,4	110,2
Annual radiation [kWh/m ² year]	1931,1	309,8	2240,9

the monthly energy of direct, diffuse and global radiation on horizontal plane-Khouribga City-

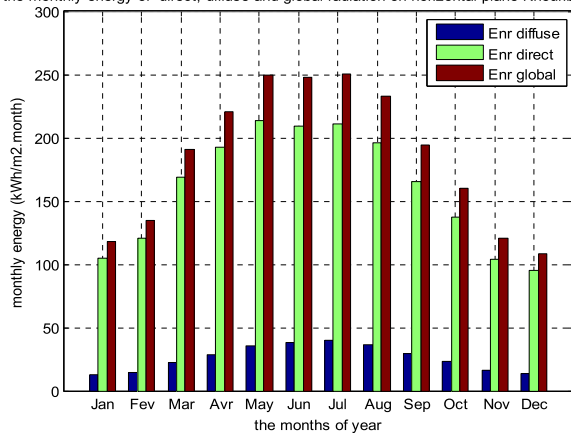


Fig. 7. Distribution of monthly energy in Khouribga.

3.4.3. Cumulative energy for each month of the year

The cumulative energy calculation is done by integrating the power formulas between sunrise and sunset. This method makes it possible to estimate the energy received by a horizontal surface. Use the same Matlab code that calculates and tracks the evolution of cumulative solar energy in each month of the year. In the figure representing the energy of solar radiation calculated for the Khouribga site, the summary of the results is given in Table 4 (see Fig. 7).

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

Table 5
The optimum inclination for each month of the year.

Months	α_{opt} tilt angle	kWh/m ² month
Jan	57°	209,6
Feb	48°	198
Mar	43°	229,9
Apr	18°	232
May	6°	250,8
Jun	0°	247,9
Jul	5°	250,7
Aug	13°	238,2
Sep	28°	218,6
Oct	43°	215,9
Nov	54°	200,1
Dec	59°	202,3
Annual radiation [kWh/m ² year]		2694

appears on the form of grouping the bars of the histogram (Torres 1 et al., 2017).

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

4. Optimum tilt of solar panels

Taking into account the above formulations, the counting energy is developed in MATLAB to derive the energy received annually, seasonal and per month. This was achieved by a simple integral calculation in a regular time interval equal to 3 min, and applied to a surface of panel 1 m² choosing inclination angles varying from 0 to 90° with step 1° (Jamil Ahmad and Tiwari, 2009; Ulgen, 2006).

A Matlab code has been developed which calculates and plots the solar energy of each month according to the inclination of a photovoltaic module.

The values of the optimum monthly angle given in the table are as follows (see Table 5).

Table 6
Seasonal and annual solar energy at seasonal tilt angle.

Period	Months	Seasonal tilt angle	kWh/m ² Season
Winter	Dec–Jan–Feb	55°	606,6
Spring	Mar–Apr–May	19°	697,8
Summer	Jun–Jul–Aug	5°	733,7
Autumn	Sep–Oct–Nov	42°	624,2
Annual radiation [kWh/m ² year]			2662,5

This allows us to deduce the optimum tilt angle of the solar panel which would lead to the maximum energy production for a given month and for a year.

The seasonal average was calculated by finding the average value of the tilt angle for each season, and the implementation of this requires that the collector tilt be changed four times in a year. In winter (December, January, and February) the tilt should be 55°, in spring (March, April, and May) 19°, in summer (June, July, and August) 5°, and in autumn (September, October, and November) 42°.

The figures showing the solar energy received for each season of the year, according to different angle of inclination and orientation of Khouribga city (see Fig. 8).

The value of the seasonal tilt angle receives the maximum of seasonal solar radiations on at this tilted surface are given in Table 6.

For fixed panels are installed in a correct position throughout the year, we can calculate the annual energy by a simple integral in a regular time interval from a surface of 1 m² with angles of inclination different from 0° to 90° and the azimuth from 60° to 300° end Determine the angle of inclination and the optimal orientation of the solar panels to access the maximum energy output (Li and Lam, 2007; Gunerhan and Hepbasli, 2007).

Accordingly, the annual solar energy yield was determined and is shown in Fig. 9. The peak value is 2524 kWh/m² which is quite good for active solar applications in Khouribga city.

When the tilt angle is beyond 30°, the annual solar yield falls slightly with increasing tilt angles. As the latitude of Khouribga city is 32°52' north, the finding supports the argument that the optimal tilt angle for solar energy collection would be very close to the angle equivalent to the latitude of the location.

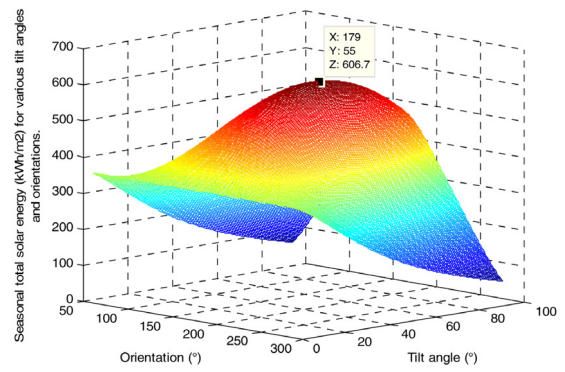
Results and discussion on optimal tilt angle in Khouribga city:

We have taken a simple mathematical model (the Eqs. (8) to (15)) to calculate the monthly, seasonal and annual average of the incident solar irradiation on a south-facing surface with a different tilt angle relative to the horizontal, from 0° to 90° with step of 1°, and this by carrying a program executed under Matlab. See the results in Table 7.

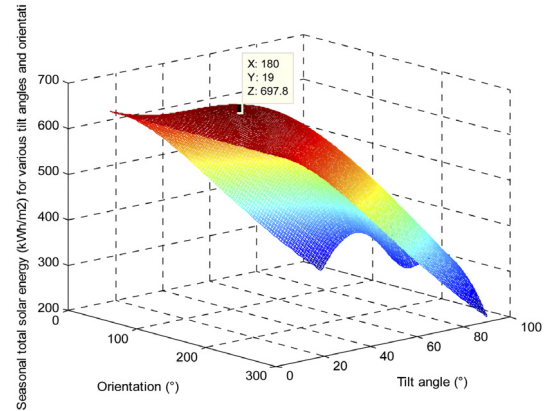
From the table, it can be seen that the maximum incident energy and that received on an inclined plane by an optimum monthly tilt angle. The choice of tilt depends on the load. For example, for solar refrigeration, the best is to get the maximum energy in summer.

So to make the most of solar irradiation, the result of the table shows that it is necessary to change the solar panels inclination each month, if this is not possible, opt for the seasonal tilt angle. The improvement of the capture efficiency by the orientation and inclination of the solar panels makes it possible to obtain a rational use of the incident solar energy, thus reducing the cost of the solar system being used.

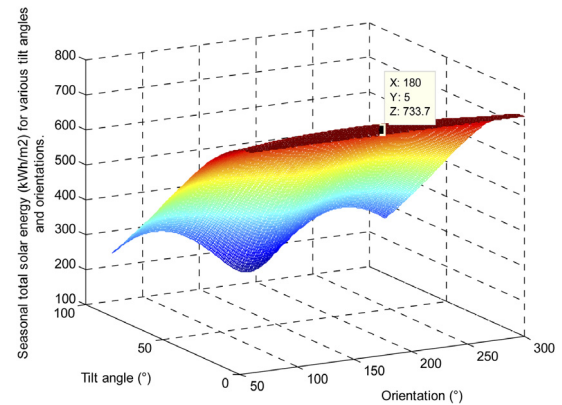
The purpose of this study was to obtain results of optimum tilt angle desired at the allotted time (monthly, seasonal and annual) to optimize the solar irradiation received by the solar panels. Khouribga in winter, the sun is low compared to the horizon, to obtain the best performance it will be necessary to favor a wide tilt angle. In spring the best tilt angle is at 19°, and in summer the optimal angle is at 5°.



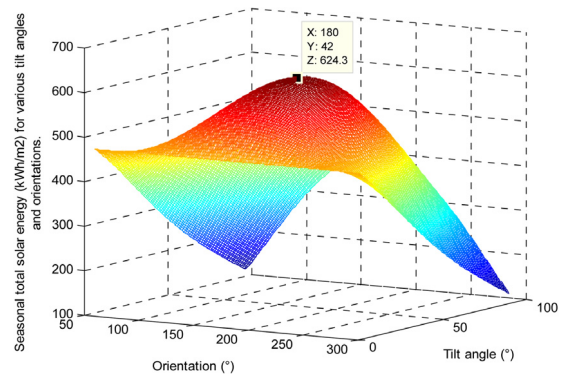
(a) Winter season.



(b) Spring season.



(c) Summer season.



(d) Autumn season.

Fig. 8. Optimal tilt angle, orientation and the solar energy received for each season of the year.

Table 7
Annual solar radiation at different tilt angle.

Optimum tilt angle	Monthly tilt angle	Seasonal tilt angle	Annual tilt angle	Horizontal surface
	2694,0	2662,5	2524,0	2240,9

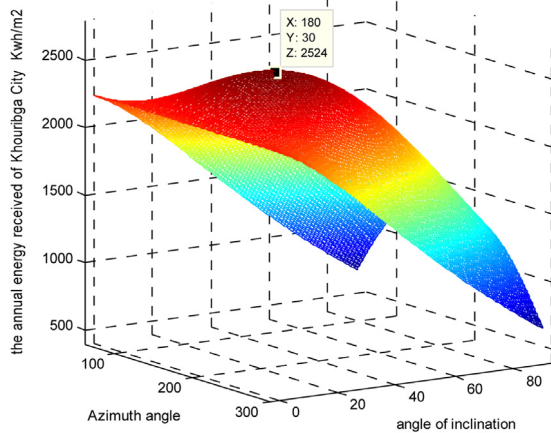


Fig. 9. Annual solar energy yield (kWh/m^2) for various tilt angles and orientations.

We can give examples of the importance of our study:

- In solar thermal:

We want to produce more heat in winter and less heat in summer. So we will try to have an optimum angle of winter, the nearest possible 55° .

- Air conditioners and solar refrigerators:

We have to optimize the receive solar irradiation in summer, as a result, it is preferable to favor production in summer, and to decrease a little the one of winter,

- In photovoltaic and thermal solar:

Electricity and hot water needs were constant throughout the year; the best inclination is therefore that of maximum sunshine, that is to say 30° .

5. Calculation of solar radiation received on the optimum tilt angle surface

We will study in this part the influence of the optimum tilt angle on the amount of solar irradiation received on a surface of 1 m^2 , in Khouribga city we used the results of previous part, the optimal tilt angle is 30° and the direction of the azimuth 180° (south).

5.1. Daily irradiation

The Matlab code that we used, allows us to calculate and plot the daily solar irradiation received on an optimal exposure surface of the typical days of each month. The results are given in Table 8.

We have added curves giving the daily variations of the solar irradiation, indicating the maximum of direct, diffuse and global solar energy arriving at a surface of optimal exposure (see Fig. 10).

The analysis of the curves obtained above indicates that the values of direct, diffuse and global solar radiation are maximum in summer and minimum in winter in Khouribga city. The global radiation energy exceeds 7000 Wh/m^2 in the summer days, on the other hand, for the winter days extend between (5700 and 7000 Wh/m^2).

the energy evolution in the year of direct, diffuse and global radiation on Opt exposure

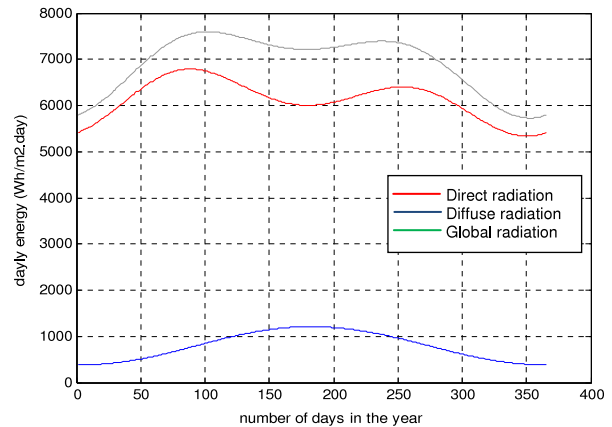


Fig. 10. Evolution of direct, diffuse and global solar radiation in the year, on optimum exposure.

the monthly energy of direct, diffuse and global radiation on Opt exposure

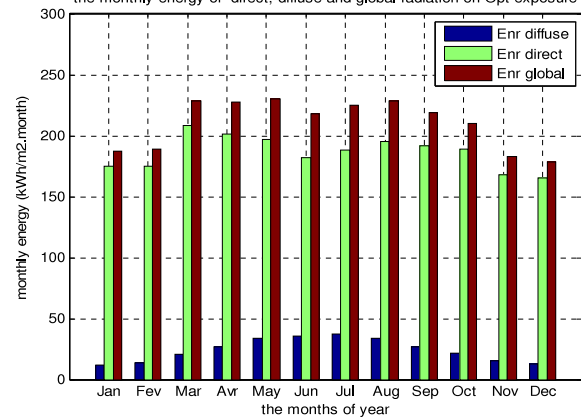


Fig. 11. The monthly direct, diffuse and global solar radiation, of optimum exposure.

5.2. The energy that accumulates for each month

We used the same calculation method of the previous part; the cumulative energy calculation is done by integrating the power formulas between sunrise and sunset. This method estimates the monthly energy received on an inclined surface of 30° and facing south. The results are shown in Fig. 11.

We can summarize the results which are given by the histogram in Table 9.

The provides information on the distribution of solar energy for each month, the energy is superior to 200 kWh/m^2 of the 8 months; corresponding the summer and intermediate months of the year, for the winter months their energy is below 200 kWh/m^2 .

In the end, we get on the global of annual energy received on a surface of the optimum tilt angle (30°) and facing south; at Khouribga city is 2524 kWh/m^2 .

Perspective the next step of our study

The climate of Khouribga province is the semi-arid and continental with hot summers and cold winters, and has a number of agricultural areas that need irrigation throughout the year, the best way to do this is to use irrigation systems of photovoltaic pumping.

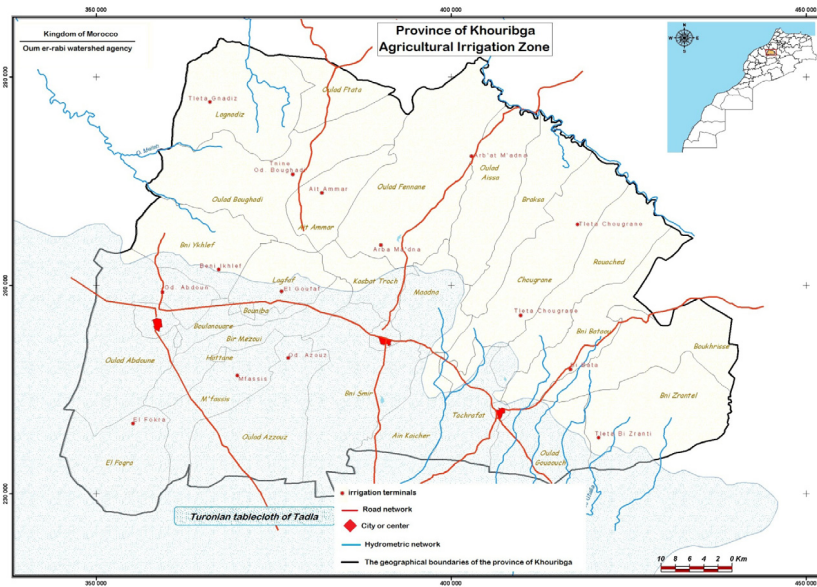


Fig. 12. Need monograph in Irrigation Water, province of Khouribga (Hydraulic Basin, 0000).

Table 8
Values of the daily irradiation of the typical days of each month.

Month	The energy received per days (Wh/m ²)				
	Days typical	No. of days	Direct energy	Diffuse energy	Total energy
January	17	17	5621	401	6022
February	16	47	6288	505	6793
March	16	75	6734	675	7409
April	15	105	6736	891	7627
May	15	135	6403	1083	7486
June	11	162	6132	1194	7326
July	17	198	6119	1207	7326
August	16	228	6323	1101	7424
September	15	258	6395	916	7311
October	15	288	6094	699	6793
November	14	318	5567	512	6079
December	10	344	5286	411	5697

Table 9
The monthly cumulative energy of optimum exposure.

Month	The energy received per month (kWh/m ²)		
	Direct energy	Diffuse energy	Total energy
January	173.08	12.33	185.41
February	173.85	13.78	187.63
March	207.54	20.74	228.28
April	201.51	26.69	228.20
May	198.19	33.60	231.79
June	183.58	35.91	219.48
July	189.82	37.17	226.99
August	195.83	33.87	229.71
September	191.27	27.27	218.55
October	188.07	21.49	209.56
November	166.60	15.20	181.80
December	164.04	12.44	176.48
All year	2233.4	290.6	2524

Our study aims to promote optimizing the use solar pumping in Khouribga province, according to the hydrological characteristics for each agricultural area in our province.

Solar pumping is characterized by a variable flow throughout the days of the year, when the photovoltaic field starts to produce electricity; the flow is produced by the pump, and it is directly related to the intensity of solar irradiation received on the photovoltaic surface.

For this reason, we have thought of maximizing the productivity of solar pump systems by integrating the seasonal tilt angle according to the borehole, the water source used and the other parameters.

6. Study of solar radiation according to the optimum tilt angle in 20 Moroccan cities

Solar radiation distribution is expressed as annual global solar energy received on a horizontal plane (in kilowatt hours per square meter per year). The 1st parameter influenced on the solar energy distribution is the latitude, that is to say the distance from the equator. Solar irradiation decreases as we get closer to the poles (or move away from the equator) (Hochberg, 2016).

Morocco has a great potential for the production of solar energy, and the (photovoltaic and solar thermal) are the two technologies favored for the exploitation of this solar potential (see Fig. 13).

The solar potential is estimated at more than 3400 MW_p. With more than 3000 h/year of sunshine, an average solar irradiation of 2500 kWh/m²/year, the Morocco enjoys a very significant solar potential (Karim and Kamilia, 2011).

Fig. 13 shows that the energy received is strongly influenced by the geographical position. During the year it is the cities of the south that receive the maximum of irradiation.

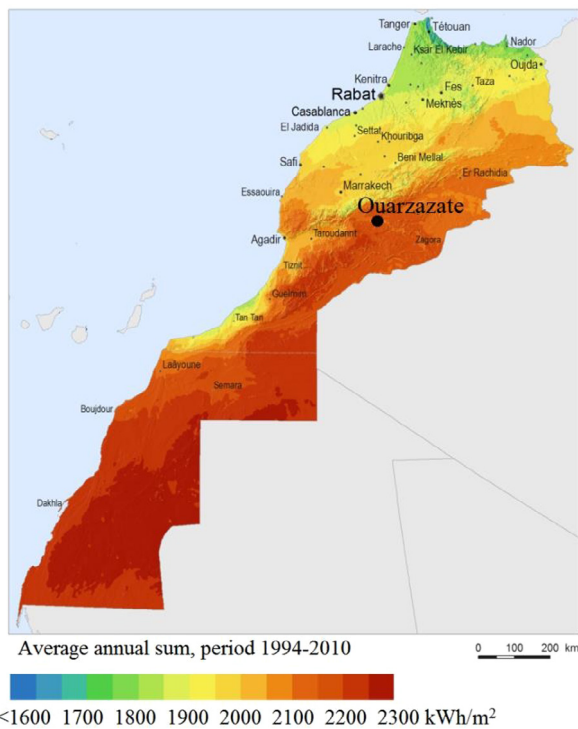


Fig. 13. Global horizontal irradiation in Morocco ($\text{kWh}/\text{m}^2/\text{year}$) (Karim and Kamilia, 2011).

Table 10
Optimum tilt angle and annual energy received.

Cities	Optimal tilt angle	Annual energy received (kWh/m^2)
Tanger	32°	2483
Oujda	31°	2488
Khouribga	30°	2524
Marrakech	27°	2541
Agadir	26°	2557

Table 10 summarizes the optimum tilt angle and the solar energy received by this angle of the four Moroccan cities from different regions, then comparing us with that which we found in Khouribga city.

From the results of Table 10 it can be seen that the optimum tilt angle for the other four Moroccan cities takes different values, and it changes when we move north or south. The optimums tilt angle increases in the cities of the north (Tangier 32° and Oujda 31°) and decreases in the cities of the south (Marrakesh 27° and Agadir 26°).

6.1. The aim of this part

In this study, we suggest the theoretical calculation of the intensity solar radiation and the availability of large spaces of all Moroccan territory.

For the purpose of realizing a solar irradiation map at the national level (IRESEN, 0000), Nanosciences and Modeling laboratory of Hassan 1st University, and in its activities, proposes a theoretical calculation method permits to construct a map of solar irradiation according to the optimum tilt angle of different 20 Moroccan cities, for the specific objectives of:

- Develop the metrology of our laboratory, with storage of the results in the database.
- Integrate the instantaneous measurements and deduce the monthly and annual productivities of the solar systems.

- Propose a method of correction and extrapolation of data to long-term.
- Propose a method to extend it to the whole of Morocco.

6.2. Results and discussions

The spatial distribution of the daily values of solar irradiation was calculated for the whole year. A finer analysis is to do this calculates month by month. The computations of the various components of the solar radiation, calculated over the whole year, it is assumed that the sky is very clear all the days of the year.

We show in Table 11 the results of annual solar irradiation values and the annual tilt angle for a different 20 Moroccan cities;

As shown in the map of Morocco (Fig. 12) and Table 11, the latitudes of the 20 Moroccan cities studied are globally between 28°N and 36°N . To ease the discussions, we have subdivided the Moroccan territory into three regions located around the three middle latitudes:

- 28° to 31°N for the south of the country: **Guelmim, Agadir, Ouarzazate, Marrakech and Errachidia.**
- 32° to 34°N for the center of the country: **Fes, Rabat, Meknes, Mohammedia, Casablanca, Ifrane, El-jadida, Settat, Beni mellal and Safi.**
- 34° to 36°N for the north of the country: **Tanger, Tetouan, Nador, Oujda and Kenitra.**

In general, the energy received from the sun takes maximum values in the cities of southern Morocco, and minimum in northern Morocco cities.

It can be seen that the solar potential recoverable on the three regions of Morocco reach respectively; $2495 \text{ kWh}/\text{m}^2/\text{year}$ in the northern region, 2518 in the center and $2550 \text{ kWh}/\text{m}^2/\text{year}$ for the south of the country.

As summarized; the values of the optimum tilt angle vary decreasing from north to south, in Morocco takes the maximum value at Tangier 32° (north of Morocco of latitude $35^\circ45'$ North and Longitude $-5^\circ800'$ West) and the minimum value at Guelmim 25° (southern Morocco of latitude $28^\circ59'$ North and Longitude $-10^\circ057'$ West).

It is obvious that the solar irradiation decreases as we get closer to the north, and the optimum angle of inclination decreases when moving away from the equator.

7. Conclusion

The tilt angles of solar panels should be adjusted monthly, seasonal or the yearly to extract the maximum energy from solar panels. In this study the optimum tilt angles for Khouribga and the 20 Moroccan cities, are calculated using the mathematical models programmed under MATLAB.

The usual recommendation for the orientation to the equator, and tilt angle of latitude should not be understood as a requirement that has a very significant impact on the installation, especially in the cities studied. We call who are interested to construct the structures dedicated to solar installations or architectural modifications, to respect these recommendations. We have established a set of diagrams and tables, allowing to quickly determining the optimum tilt angle of different 20 Moroccan cities.

Finally, the yearly average optimum tilt angle in Morocco varies between 28° and 32° . This angle can be used for fixed installations or for building applications.

Table 11
Annual solar radiation, according to optimum tilt angle in 20 Moroccan cities.

Cities	Geographical data		Optimal tilt angle	Annual energy received (kWh/m ²)
	Latitude	Longitude		
Tanger	35°45'N	−5.800 W	32°	2483,27
Tetouan	35°34'N	−5.366 W	32°	2512,52
Nador	35°10'N	−2.933 W	31°	2484,67
Oujda	34°41'N	−1.911 W	31°	2487,80
Kenitra	34°15'N	−6.578 W	30°	2506,03
Fes	34°02'N	−5.000 W	30°	2505,70
Rabat	34°01'N	−6.841 W	30°	2509,71
Meknes	33°53'N	−5.554 W	30°	2508,78
Mohammedia	33°41'N	−7.382 W	30°	2514,91
Casablanca	33°32'N	−7.583 W	30°	2517,08
Ifrane	33°31'N	−5.116 W	30°	2512,40
El-jadida	33°14'N	−8.500 W	29°	2522,40
Settat	33°00'N	−7.616 W	29°	2523,73
Beni mellal	32°20'N	−6.360 W	28°	2530,35
Safi	32°17'N	−9.233 W	28°	2534,60
Errachidia	31°55'N	−4.424 W	28°	2530,92
Marrakech	31°37'N	−8.008 W	27°	2541,19
Ouarzazate	30°55'N	−6.893 W	27°	2548,29
Agadir	30°25'N	−9.600 W	26°	2556,95
Guelmim	28°59'N	−10.057 W	25°	2573,30

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