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Global Solar Radiation Estimation on a Horizontal and Tilted Plane in Agadir City, Morocco

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ABSTRACT
This paper proposes the modeling and simulation of the incident solar radiation on a horizontal and inclined plane in the city of Agadir. To do, we adopt the Kasten model which takes the atmospheric turbidity into consideration in order to estimate the incidental solar radiation on a horizontal plane. In addition we determine the incident solar radiation on an inclined plane from the global horizontal radiation. To validate the chosen models, we compare the simulated values of the solar radiation with the experimental measurements given by the installed CRX10 Campbell meteorological station in our laboratory.

General Terms
Prediction of solar radiation.

Keywords
Prediction; Solar radiation; Kasten model; Klucher model.

1. INTRODUCTION
Renewable energy resources have enormous potential and can satisfy the present and future energy demand. This resource can enhance diversity in energy supply markets, secure long-term sustainable energy supply, and reduce local and global atmospheric emissions [1], In particular, reducing greenhouse gases emissions from electricity and heat generation [2]. An estimation of the amount of incident solar radiation on an area is usually required for many solar energy applications. Consequently, for this estimation, several radiation models have been proposed [3,9].

This paper proposes the modeling and simulation of the incident solar radiation on a horizontal and inclined plane in the city of Agadir. The sections of our paper are: introduction, the meteorological data, modeling and finely a conclusion.

2. THE METEOROLOGICAL DATA
Meteorological data, such the irradiation data and temperature are delivered from the data logger CRX10X installed at the superior school of technology in Agadir (Fig. 1). This station is equipped with various sensors for the acquisition of global and diffuse irradiation, the ambient temperature, humidity and speed and wind direction. The measured values can be presented in different forms (average, maximum, minimum, …), depending on the chosen configuration. The used data in this work are related to the site of Agadir, whose geographical coordinates are: □ = 9.579 °W for the Longitude, L = 30.406 °N for the latitude and Z = 41 m for the altitude.

Fig 1: Meteorological station with the data logger Campbell CR10X

3. MODELING
3.1 The sun declination
The sun declination δ is the angle between the rays of the sun and the plane of the earth's equator. It's expressed as a function of day number n by the following formula [10]:

$$\delta = 23.45\sin\left[360*\left(284+n\right)/365.25\right] \quad (1)$$

3.2 Hour angle
The hour angle H is the solar angular displacement east or west of the local meridian due to the rotation of the earth (15° per hour). The hour angle is negative in the morning and positive afternoon. Therefore, the hour angle can be written as follows [1]:

$$H = 15°(RTS - 12) \quad (2)$$

Where *RTS* is real time solar (in hours) .It is counted from 0 to 24 h. It is calculated by the following relationship:

$$RTS = T_{legal} + ET - \frac{L - L_{ref}}{15} - C \quad (3)$$

Where T_{leg} is the legal Time, *C* is the jet lag, L-L_{ref} is the difference in longitude between the place and the considered as the reference time legal and *ET* is is the correction of the time equation, due to the variation of the earth speed on its path around the sun. It can be calculated by the following expression:

$$\begin{aligned} ET &= -0.0002 + 0.47497\cos(x) - 7.3509\sin(x) \\ &\quad -3.2265\cos(2x) - 9.3912\sin(2x) \\ &\quad -0.0903\cos(3x) - 0.3361\sin(3x) \end{aligned} \quad (4)$$

Where:

$$x = 360n/366 \quad (5)$$

3.3 Solar coordinates (zenithal and azimuth angles, altitude)

The zenith angle θz is defined as the angle between the vertical and the line to the sun, which is the angle of incidence of a beam radiation on a horizontal plan, it's can be calculated as [1]:

$$\cos(\theta_z) = \cos(\delta)\cos(\varphi)\cos(h) + \sin(\varphi)\sin(\delta) \qquad (6)$$

The solar altitude angle h is the angle between the horizontal and the line to the sun that is the complement of the zenith angle. It can be expressed using the following equation:

$$\sin(h) = \cos(\delta)\cos(\varphi)\cos(H) + \sin(\varphi)\sin(\delta) \qquad (7)$$

The solar azimuth angle as is defined as the angular displacement from south of the projection of beam radiation on horizontal plan [1]. It can be calculated as:

$$\begin{aligned} a_s &= \arcsin\left(\cos(\delta)\sin(H)/\cos(h)\right) \\ &\qquad if \quad \cos(h) \geq \tan(\delta)\tan(L) \\ a_s &= 180 - \arcsin\left(\cos(\delta)\sin(H)/\cos(h)\right) \\ &\qquad if \quad \cos(h) \prec \tan(\delta)\tan(L) \end{aligned} \qquad (8)$$

3.4 Incidence angle

The incidence angle θ_i is the angle between the beam radiation and the normal to the surface with any orientation. It can be expressed using the following equation:

$$\begin{aligned} \cos(\theta_i) &= \sin(\delta)\sin(\varphi)\cos(\beta) \\ &\quad - \sin(\delta)\cos(\varphi)\sin(\beta)\cos(a_p) \\ &\quad + \cos(\delta)\cos(\varphi)\cos(\beta)\cos(H) \\ &\quad + \cos(\delta)\sin(\varphi)\sin(\beta)\cos(a_p)\cos(H) \\ &\quad + \cos(\delta)\sin(\beta)\sin(a_p)\sin(H) \end{aligned} \qquad (9)$$

Where a_p is the surface azimuth which is the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, β referred also the surface inclination.

3.5 Global radiation modeling on the horizontal plane

The global radiation G on horizontal plane is the sum of diffuse radiation G_{diff} and the direct radiation G_{dir}. It expressed as follows:

$$G = G_{dir} + G_{diff} \qquad (10)$$

The beam radiation G_{dir} is defined as solar radiation that travels from the sun to the earth's surface without any scattering by the atmosphere [1]. It can be expressed using the following equation [11]:

$$G_{dir} = (I_0)_{ext} \exp\left[-\frac{m_h T_L}{0.9 m_h + 9.4}\right]\sin(h) \qquad (11)$$

Where m_h is the atmospheric optical distance, called air mass (m). It can be written as follows:

$$m_h = \frac{1 - 0.1Z}{\sin(h) + 0.15\left(h + 3.885\right)^{-1.253}} \qquad (12)$$

T_L is the Linke turbidity factor. It gives an evaluation of the atmospheric extinction by gaseous molecules and aerosols. Its average value is given by the following expression [12]:

$$T_L = 2.5 + 16\beta_A + 0.5\ln(w) \qquad (13)$$

β_A is the Angstrom coefficient and w is the height of condensable water (β_A = 0.05 and w = 1 cm for a clear sky).

The diffuse radiation G_{diff} is solar reaching the earth's surface after having been scattered from the direct solar beam by molecules in the atmosphere. It can be expressed using the following equation:

$$G_{diff} = \frac{(I_0)_{ext}}{25}\sqrt{\sin(h)}\left[T_L - 0.5 - \sqrt{\sin(h)}\right] \qquad (14)$$

3.6 Global radiation modeling on tilted planes

The global radiation on a tilted surface G_β is the sum of the diffuse radiation $G_{diff,\beta}$, beam radiation $G_{dir,\beta}$, and the ground reflected radiation $G_{ref,\beta}$. Therefore, the incident global radiation on tilted surface is given by the following expression [11]:

$$G_\beta = G_{dir,\beta} + G_{ref,\beta} + G_{diff,\beta} \qquad (15)$$

The beam radiation on tilted surface $G_{dir,\beta}$ can be estimated by multiplying its value on a horizontal surface G_{dir} by a geometric factor R_b which depends on the zenith and incidence angles. It's expressed as:

$$G_{dir,\beta} = G_{dir} R_b = G_{dir}\frac{\cos(\theta_i)}{\cos(\theta_z)} \qquad (16)$$

The ground reflected radiation is assumed as follows [13]:

$$G_{ref,\beta} = \frac{1}{2}\rho G\left(1 - \cos\beta\right) \qquad (17)$$

According to the Klucher model [14], the diffuse solar radiation on tilted planes can be given by the following expression:

$$\begin{aligned} G_{diff,\beta} &= G_{dir}\left[0.5\left(1 + \cos(\frac{\beta}{2})\right)\right]\left[1 + \left(1 - \left(\frac{G_{diff}}{G}\right)^2\right)\sin^3(\frac{\beta}{2})\right] \\ &\quad \times\left[1 + \cos^2(\theta_i)\sin^3(\theta_z)\right] \end{aligned} \qquad (18)$$

4. RESULTS AND DISCUSSIONS

In order to validate the used model to predict the global solar radiation received by a horizontal surface, we considered a sample of recorded measurements by the installed meteorological station in the site under study. This measurement covers a long period from 2009 to 2013. Figures 1 and 2 provide a comparison between this solar radiation with that delivered by our model developed under Matlab for the days of July 1st 2011 and March 12th 2012. In order to judge the reliability of the proposed model at our site and to determine the error of the incident radiation, we calculate the committed instantaneous relative error using the equation (19):

$$Err = \frac{G_{measured} - G_{calculated}}{G_{measured}} \quad (19)$$

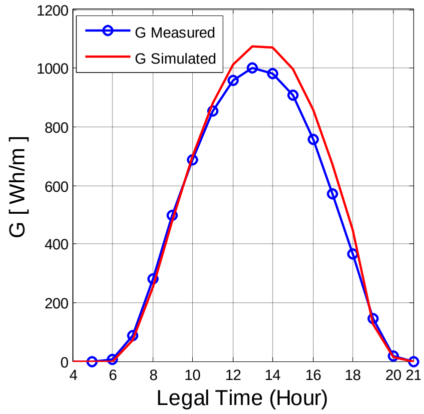

Figure 2: Global solar radiation on a horizontal surface for July 1st 2011

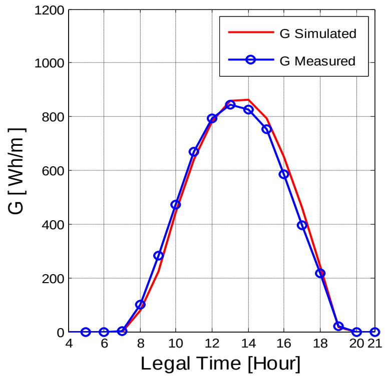

Fig. 3. Global solar radiation on a horizontal surface for March 12th 2012

The values of this error for both days of the selected sample are shown in Figure 3. These values show that the instantaneous relative error does not exceed 10 % between 10 AM and 15 PM, with a maximum value of -22 % for the day of March 12th 2012 at 18 PM. This shows that our model gives satisfactory results, allowing its validity. For inclined surfaces of an angle β = 15, 30, 45 and 60 °, we represent in Figure 4 the received global solar irradiance G on these surfaces. We notice an increase in received solar radiation by surfaces inclined relative to horizontal surfaces. Our simulation shows that the solar irradiance is proportional to the angle of inclination.

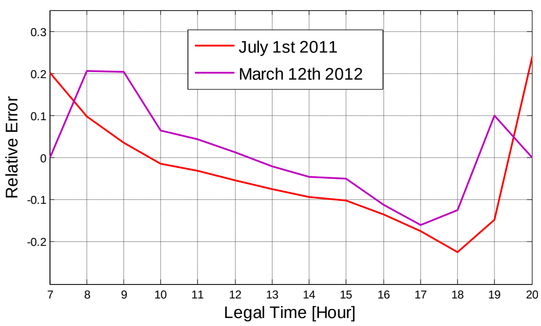

Figure 3: Relative error of the global solar radiation on a horizontal surface for both selected days

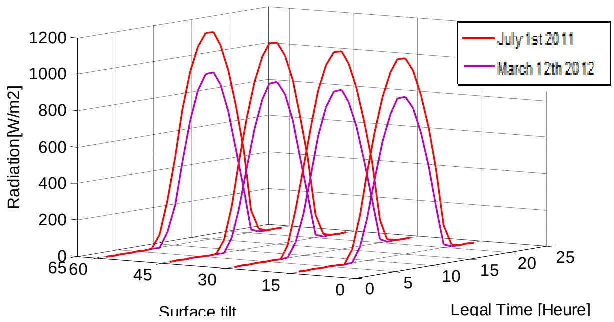

Figure 4: Global solar radiation for different angles and for both selected day

5. CONCLUSION

This work presents the estimation of solar radiation on a horizontal plane as well as an inclined one with using a Kasten model. The collected measurements by the installed meteorological station in our laboratory, have allowed validating the chosen model for the prediction and estimation of incident solar radiation on horizontal surfaces. According to simulations, the proposed model and validated by measures, provides that the solar irradiance is proportional to inclination angle.

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