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Global solar radiation on tilted surfaces in Tunisia: Measurement, estimation and gained energy assessments

A. Ben Othman [a,c], K. Belkilani [a,b,*], M. Besbes [a,b]

[a] Robotics, Informatics and Complexes Systems, Laboratory LR16ES07, (RISC), National School of Engineers of Tunis, University of Tunis El Manar, Tunisia
[b] Higher Institute of Information and Communication Technologies, University of Carthage, Tunisia
[c] National School of Engineers of Carthage, University of Carthage, Tunisia

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ABSTRACT

A very important factor in the assessment of solar potential for the installation of photovoltaic plants is the availability of global irradiation data measurements. Such data must be collected over a period of time longer than 11 years and must be accurate. In some countries, it is difficult to have databases of these measures. To overcome this problem, we propose, the use of numerical models to estimate the monthly, seasonally and annually solar energy irradiation (global diffuse and direct solar radiation), especially on tilted surface.

The results obtained from the numerical models are compared to the data collected from three regions on Tunisia: Bizerte (in the north), Nabeul (near to the north east) and Djerba (in the south).

The actual measurements taken from the meteorological stations and the measurements generated by the numerical models are very close.

After the validation of the numerical models, we tried to calculate the best tilt angle for each period of the year to position a photovoltaic panel, in a given region, to reach maximum energy recovery.

The practical validation, of the optimal tilt angle search and the adequate period, was conducted at the Research and Technology Center of Energy of Borj Cedria. The obtained results are satisfactory and prove the reliability of the constructed numerical models.

1. Introduction

Solar energy resource data is necessary for the evaluation of the profitability of installing photovoltaic plants. However, the real energy produced cannot be predicted because the energy generation process depends on climatic conditions (Tadros, 2000). The total solar radiation data is scarce in some locations, this is due to the absence of meteorological measurement stations and remote data collection networks, whose installation is expensive (Codato et al., 2008). Research and development efforts are required to ameliorate estimation processes to reach accurate predictions (Deshmukh, 2008; Ashraful Islam et al., 2016; Derouich et al., 2014).

Total measured solar radiation data are the best source of information for estimating average incident radiation necessary to calculate the productivity of an installed solar energy systems. In order to evaluate the production of a photovoltaic solar power plant, in a given region, measurements must be made over a period of at least 11 years. Generally, these measures are only available in developed countries (Li et al., 2008; Sebaii et al., 2010; ElMghouchi et al., 2014).

To trap the maximum amount of solar radiation, it is possible to use photovoltaic panels powered and driven by a sun system tracking. These panels are often expensive and require excessive maintenance. However, a more cost-efficient method would be the implementation of a periodically-changing (either monthly or seasonally) optimum tilt angle. This period can be monthly or seasonally. The value of the tilt angle and position-shifting periods have always been determined by the measurements collected over tens of years. In the absence of these data, it is possible to use numerical models of prediction.

The measurement of solar radiation falling on tilt surface is important to estimate solar radiation in locations where there are no facilities to measure any meteorological data (Loutzenhizer et al., 2007). Studies on and measures in this field are rare (Pandey and Katyar, 2009; Miguel et al., 2001; Despotovic and Nedic, 2015). In this case, various radiation models for inclined surfaces have been proposed. Some of they include isotropic models (Liu and Jordan, 1960; Duffie and Bechman, 1991; Farhan et al., 2015) anisotropic models (Perez et al., 1986; Yao et al., 2015) and models for clear sky (Robeldo and Soler, 2002; Badescu, 2002). The total radiation

* Corresponding author at: Higher Institute of Information and Communication Technologies, University of Carthage, Tunisia.
E-mail address: kaouther.belkilani@istic.rnu.tn (K. Belkilani).

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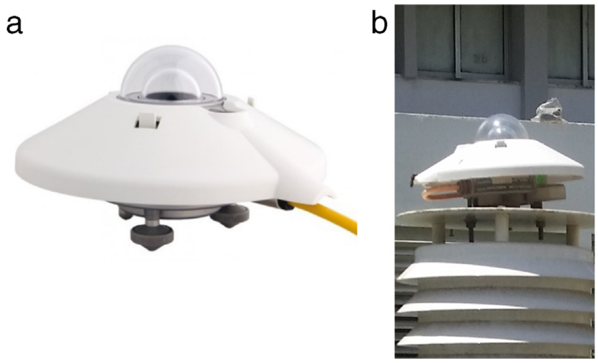

Fig. 1. CMP 3 Pyranometers for global irradiance measurements. *Source:* (a) (kipp_Zonen_booklet _Pyranometers) (b) (National Institute of Meteorology of Tunisia.)

Fig. 2. Meteorological station energy systems of the National Institute of Meteorology of Tunisia.

Table 1
CMP3 pyranometer specifications.

Spectral range (50% points)	300 to 2800 nm
Sensitivity	5 to 20_V/W/m^2
Impedance	20 to 200_
Maximum operational irradiance	2000 W/m^2
Response time (63%)	<6 s
Response time (95%)	<18 s

on tilt surface consists of three components: beam, reflected radiation from the ground and diffuse radiation (Noorian et al., 2008; Notton et al., 2006; Maleki et al., 2017). Each one of these models predicts beam and diffuse components and global solar radiation. Hence, the possibility to estimate the incident radiation on tilted surface (Hameed et al., 2017).

All meteorological stations, of the National Institute of Meteorology of Tunisia, measure global solar radiation intensities only on horizontal surface (Evseev and Kudish, 2009). The recorded data are only the monthly averages. To overcome the problem of data scarcity, we propose in this paper, a numerical model to calculate the optimal tilt angles and to calculate the duration of holding of each angle in function of the losses to be gained in the energy production.

This paper is divided into two parts:

In the first part, we discuss in detail the construction of the numerical model. Then we evaluate the validity of the generated results in comparison with the meteorological data received from, three remote stations in different Tunisian cities, Bizerte in the north, Nabeul in the north east and Djerba in the south.

The second part is devoted to the evaluation of profit losses, engendered by the installation with fixed inclination of photovoltaic panels.

2. Model synthesis

2.1. Measurement instruments

Measurements are made by pyranometers (global solar radiation) (see Fig. 1). They are radiometers designed to measure the global irradiance on a plane surface resulting from radiant fluxes in the wavelength ranging from 300 to 2800 nm. The received radiation is converted into heat by the blackened surface. The temperature variation between the blackened surface and the body of the instrument is proportionate to the irradiance of the global solar radiation, as is measured by several thermocouples (see Table 1).

We used the data obtained from the three stations Bizerte, Nabeul and Djerba. Fig. 2 is a photo that shows the meteorological station energy systems of the National Institute of Meteorology in the Tunis DC. The data of global solar radiation measured (in KWh /m^2) in the three meteorological stations was collected over the period between January and December of the year 2015.

2.2. Assumptions

In this work, we present the basic solar equations in detail and the empirical relations that can be, consequently be utilized to compute global irradiance as a result. We recall the main equations which are detailed in Duffies and Bechman (2006) and Stone (1993).

The Solar radiation which reaches the ground is formed by a direct radiation (I^*) and a diffuse radiation (D^*) which together form the global radiation. The sum of these components equates to the total irradiance (G^*). All these are calculated in W/m^2.

2.2.1. Solar energy

The earth receives daily a large flow of solar energy. The power of this radiation depends on several criteria, meteorological conditions, atmospheric diffusion (phenomena of dispersion, reflection and absorption). The average amount of solar radiation received at any earth's surface, is about 1367 W/m^2 (Wong and Chow, 2001). This total radiation energy is called solar constant.

The energy received depends on the day of the year and can be calculated using the following formula:

$$E_{sol} = 1367 \times (1 + 0.00334 \times \cos(360 \times (j - 2.7206)/365.25)) \quad (1)$$

j: the order number of the day in the year ranging from 1 on January to 365 on 31 December.
for example, 1 January = 1, 20 February = 51, and so on.

A. Latitude and longitude

Latitude (*Lat*) is the angle formed by the equatorial plane and the vector "center of the earth → local point". Longitude (*Lon*) is the angle formed by the meridian of reference (Greenwich meridian) and the meridian of the local point. The angle is negative to the west and positive to the east. As the earth takes 24 h to spin around its axis (360°) each hour represents 15 degrees of longitude deviation and therefore each degree of longitude represents 4 min.

B. Declination

Declination (*Dec*) is the angle formed by the vector "center of the earth → sun" and the equatorial plane of the earth. Moreover, the declination is the angular distance from the sun north or south