Renewable Energy 35 (2010) 2452–2460

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Practical models to estimate horizontal irradiance in clear sky conditions: Preliminary results

Germán A. Salazar [a,b,*], Alejandro L. Hernández [a,b], Luis R. Saravia [a,b]

[a] Department of Physics, School of Exact Sciences, National University of Salta, Bolivia Avenue #5150, 4400 Salta Capital, Argentina
[b] INENCO (Institute of Non Conventional Energy Research), Bolivia Avenue #5150, 4400 Salta Capital, Argentina

A R T I C L E I N F O

Article history:
Received 6 November 2009
Accepted 13 January 2010
Available online 29 March 2010

Keywords:
High altitude sites
Horizontal irradiance model
Clear sky model
Andean region

A B S T R A C T

The Argentinean Northwest (ANW) is a high altitude region located alongside Los Andes Mountains. The ANW is also one of the most insolated regions in the world due to its altitude and particular climate. However, the characterization of the solar resource in the region is incomplete as there are no stations to measure solar radiation continuously and methodically. With irradiance data recently having been measured at three sites in the Salta Province, a study was carried out that resulted in a practical model to quickly and efficiently estimate the horizontal irradiance in high altitude sites in clear sky conditions. This model uses the altitude above sea level (A) as a variable and generates a representative clearness index as a result ($k_{t\text{-R}}$) that is calculated for each site studied. This index $k_{t\text{-R}}$ is then used with the relative optical air mass and the extraterrestrial irradiance to estimate the instantaneous clearness index (k_t). Subsequently, the index $k_{t\text{-R}}$ is corrected by introducing the atmospheric pressure in the definition of relative optical air mass proposed by Kasten. The results are satisfactory as errors in the irradiance estimations with respect to measured values do not exceed 5% for pressure corrected air masses $AM_c < 2$. This model will be used in a feasibility study to locate sites for the installation of solar thermal power plants in the ANW. A prototype of a CLFR solar power plant is being built in the INENCO Campus, at the National University of Salta.

1. Introduction

Solar energy is a renewable energy source that is beginning to be exploited to generate massive amounts of electric energy. Solar thermal power plants have been built worldwide using the best known designs: parabolic, power tower, dish and compact linear Fresnel reflectors (CLFR) [1].

A very important aspect in the design of any thermal power plant is the evaluation of the solar resource [1–4]. For CLFR systems, this information leads to the modeling of atmospheric transmittance and the calculation of the direct normal irradiance [5]. This will determine the influence of atmospheric parameters, such as aerosols and clouds, in the rate of steam production.

The ANW is included within one of the most insolated zones on Earth and certainly in the Americas (Fig. 1). This extremely insolated region can be found in Argentina, Chile, Bolivia and Peru, amongst others. These are developing countries and lack both the necessary instruments and budget for the detailed and systematic study of the characteristics of the solar radiation incident on the region. Despite this disadvantage, many local researchers have made significant efforts to remedy this lack of information through studies in small areas coupled with extrapolation of the results to larger areas. This is the methodology used in this work.

To characterize the incident solar radiation in the area belonging to Argentina, an empirical model was developed to estimate the horizontal irradiance (and irradiation) for clear skies using as independent variables; the altitude A above sea level, the geographical coordinates and the day of the year. This model emerges from the irradiance data taken for at least a year at three sites within the ANW: Salta City, Tolar Grande and El Rincon Salar, shown in Fig. 1.

While there are many ways to estimate solar radiation (by isotropic models [6–8], anisotropic models [9–16] or atmospheric radiative transfer models [17–20]), local researchers often lack the data necessary to introduce such models (air transmittance, absorption coefficients, water vapor column and diffuse radiation factors). The presented models are useful and efficient tools to obtain accurate values of horizontal global solar irradiance in a fast and easy way.

* Corresponding author.
E-mail address: germansalazar.ar@gmail.com (G.A. Salazar).

0960-1481/$ – see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.renene.2010.01.033

Nomenclature

θ_z	Zenith solar angle
A	Altitude above sea level (meters).
AM	Relative optical air mass, defined as $1/\cos\theta_z$
AM_c	Atmospheric pressure corrected for relative optical air mass AM_K
AM_K	Relative optical air mass, as defined by Kasten (1966)
G	Horizontal global irradiance (W/m^2)
G_0	Horizontal global extraterrestrial irradiance (W/m^2)
$G_{e,i}$	ith estimated horizontal global irradiance value (W/m^2), obtained using the ith measured G_i irradiance value and altitude A. The minimum value of RMSE between these irradiances determines the value of the constant c_1, which in turn determines the value of $k_{t\text{-R}}$
H	Daily horizontal global solar irradiation (MJ/m^2)
H_0	Daily horizontal global extraterrestrial solar irradiation (MJ/m^2)
K_t	Daily clearness index
k_t	Instantaneous clearness index
$k_{t\text{-R}}$	Altitude representative clearness index, obtained using AM air mass
$k_{t\text{-R-p}}$	Altitude representative clearness index, obtained using AM_c air mass

Other aspects considered in this study of solar radiation, such as, daily and instantaneous clearness index definitions, atmospheric transmission coefficients and some issues of solar geometry will be discussed as they arise.

2. General characteristics of solar resource in the region

There are four areas in the world that exhibit the highest mean values of global horizontal solar irradiation: Africa, Australia, North and South America [21]. Except for South America, the other continents have thermal power plants in various stages of installation and tuning. INENCO has begun to build the first native CLFR system for massive electricity generation. In parallel, a quantitative study of the solar resource of the region has begun with the aim of determining the best places to install the final version of the CLFR prototype.

In Fig. 1, the region showed in the red square includes the west side of Jujuy Province, the central and west side of Salta province and the north of Catamarca Province, all in ANW. This zone, called JSC in this paper (highlighted in white in Fig. 1), is characterized by its high altitude (over 1000 m). In the Solar Energy Atlas of Argentina (SEAA) [22], the annual average monthly global irradiation in the JSC zone is approximately 5.83 kWh/m^2; this is equivalent to 2.13 MWh/m^2 per year.[1] The hours the sun is shining (sunshine hours or heliophany) is also high: the annual daily average is 8.5 h. In the SEAA, the geographic distribution of the monthly global iso-irradiation lines was calculated using the kriging method [23], but if solar irradiation or irradiance values for a specific site inside the region are needed, a new estimation method would be necessary. The empirical models presented here tries to fulfill this characterization using the altitude A above sea level as the main variable.

[1] The solar energy that impinges on an area of 41 km^2, in the JSC zone, would be sufficient to meet the entire annual needs of Argentina.

However, not only the solar resource must be taken into account in order to decide the location of a solar thermal power plant. The proximity to power grids, roads, towns and sources of soft water, the weather, the environmental impact, etc, are all important factors to be considered [5]. There is a need for a feasibility analysis with all the information available on actual or estimated irradiance data to avoid errors in logistics and designs. The empirical model estimates global solar irradiance on sites that have been previously identified as potential or feasible for their proximity to the basic infrastructure mentioned above.

After this selection, measurements of direct and global solar radiation along with meteorological parameters must be performed in the pre-chosen places. This allows characterizing the attenuation by aerosols and determining the frequency of cloud cover and general behavior of meteorological variables.

3. The empirical high altitude irradiance model: definitions and premises

The possibility of estimating horizontal irradiance values using only two simple equations was recently proposed for Bogotá City [24]. The capital of Colombia is located 2580 m above sea level. Quoting other researchers [25,26], Forero et al. [24] proposed an empirical equation to estimate the instantaneous clearness index k_t and/or the global irradiance G on horizontal surfaces as

$$k_t = \frac{G}{G_0} = 0.7^{\mathrm{AM}^{0.678}} \tag{1}$$

where AM is the relative optical air mass estimated as $1/\cos\theta_z$, θ_z is the zenith angle, G is the measured horizontal global irradiance and G_0 is the horizontal extraterrestrial global irradiance. Forero et al. [24] noted that equation (1) gives very good results for measurements taken at sea level, but at higher altitudes the correlation decreases. Equation (1) is valid only for sites at sea level.

Under clear sky conditions, the attenuation of solar radiation is caused by the effects of absorption + dispersion. These effects can be considered together by using Lambert–Beer–Bouguer law [27]. To study changes in the attenuation by absorption + dispersion due to changes in altitude, Forero et al. [24] proposed a new relation, shown in equation (2), which maintains the form of equation (1) and adds terms similar to those used in Lambert–Beer–Bouguer law. In equation (2), it is assumed that the spectral coefficients of dispersion and absorption are indistinguishable for a clear atmospheric day [24].

$$k_t = \frac{G}{G_0} = \left(1 - e^{-\left(c_1 A + \tau^a + \tau^d\right)}\right)^{AM^{0.678}} = \left(1 - e^{-(c_1 A + c_2)}\right)^{AM^{0.678}} \tag{2}$$

where c_1 is a constant that multiplies the altitude A of the site of measurement and c_2 is a constant related to the values of the broadband integrated spectral optical thickness coefficients τ^a for absorption and τ^d for dispersion.

The terms "absorption" and "dispersion" are related to the effects that occur in extraterrestrial solar radiation when it passes through Earth's atmosphere. The term "reflected" might be considered more accurate than "dispersion" as it refers to the solar radiation coming from the whole sky, but as this paper does not separate the measured global radiation in direct and diffuse components, we continue using the term "dispersion" to engage the atmospheric effects, over extraterrestrial solar radiation, that generate the diffuse solar radiation.

The main idea is that expression $1 - e^{-(c_1 . A + c_2)}$ is a type of *corrected-by-altitude* instantaneous clearness index related to the absorption + dispersion coefficients of the Lambert–Beer–Bouguer law, broadband integrated. The goal of equations (1) and (2) is to