Renewable Energy 60 (2013) 293–301

Contents lists available at SciVerse ScienceDirect

Renewable Energy

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

A climatological estimate of incident solar energy in Tamaulipas, northeastern Mexico

David Rivas [a,*], Salomón Saleme-Vila [b], Rogelio Ortega-Izaguirre [c], Fabio Chalé-Lara [b], Felipe Caballero-Briones [b]

[a] Departamento de Oceanografía Biológica, CICESE. Carr. Ensenada-Tijuana #3918, Zona Playitas, 22860 Ensenada, Baja California, México
[b] Instituto Politécnico Nacional, Laboratorio de Materiales Fotovoltaicos, CICATA-Altamira. Km 14.5 Carretera Tampico-Puerto Industrial Altamira, 89600 Altamira, Tamaulipas, México
[c] Instituto Politécnico Nacional, Ciencias Oceánicas y Atmosféricas Aplicadas, CICATA-Altamira. Km 14.5 Carretera Tampico-Puerto Industrial Altamira, 89600 Altamira, Tamaulipas, México

ARTICLE INFO

Article history:
Received 4 January 2013
Accepted 8 May 2013
Available online 7 June 2013

Keywords:
Incident solar energy
Northeastern Mexico
Climatology
Estimation
Empirical model

ABSTRACT

An estimation of climatological fields of incident solar energy in Tamaulipas State, northeastern Mexico, is presented. Monthly mean evolution of solar energy in 7 automatic meteorological stations distributed along the State shows that the maximum values generally exceed 500 ± 200 W m^{-2} during fall-winter (Nov–Feb), and 700 ± 200 W m^{-2} during spring-summer (May–Aug). An empirical model, which estimates the solar energy as function of other climatic variables (minimum temperature, maximum temperature, evaporation, and precipitation) recorded in 165 climatological conventional stations, is used to extend the climatological solar-energy estimate in the study area. The mean values of both measured and estimated solar energy are objectively mapped to fill the observation gaps and reduce the noise associated with inhomogeneous statistics and estimation errors. The highest values of solar energy (~6.7 kW h m^{-2} during the summer and ~4.0 kW h m^{-2} during the winter) are observed in the highlands, southwestern part of the State, whereas the lowest values (~5.7 kW h m^{-2} during the summer and ~2.8 kW h m^{-2} during the winter) are observed in the south-central part of the State.

1. Introduction

Amongst the most promising energy resources are the photovoltaic and photo thermal energies. Particularly, photovoltaic energy is becoming one of the most dynamic research fields (Rockett [1]) as well as an increasingly important market, with an exponential growth rate in the last 10 years that led to a doubling from 2009 to 2010, ending with an installed capacity of about 39 GW in 2010 (Jäger-Waldau [2]). The foremost regions in photovoltaic electricity generation are by far the European Union and the United States, although the Asian-Pacific region is also experiencing a huge increase in photovoltaic investments (Jäger-Waldau [2]). In Mexico, the current photovoltaic installed capacity is only about 40 MW at the end of 2012, as reported by Mexico's Secretariat of Energy (SENER [3]). Solar photovoltaic systems are considered a priori a very reliable source of electricity due to non-fuel costs, long term duration and no emissions during operation. In order to determine the feasibility of both government and private investments, trusty calculations of the solar energy incidence are required as a prerequisite of a cost-benefit calculation that would determine the final decisions of the policy makers or investors. This kind of studies have been conducted in countries of the Sun Belt such as Pakistan (Khalid and Junaidi [4]), Corsica (Haurant et al. [5]), Cyprus (Makrides et al. [6]), Turkey (Toklu [7]) or Australia (Bahadori and Nwaoha [8]), as well as in northern USA states such as Wisconsin (Myers et al. [9]). Although current electricity tariffs, investment costs, existence of government subsidies/programs and other factors have been considered in those analyses, the availability of the solar resource is by far one of the most important.

The mean irradiation in Mexico has been estimated from low-resolution irradiance maps to be around 5.5 kW h m^{-2} d^{-1}, varying between 3 and 8.5 kW h m^{-2} d^{-1} during the year and over the territory (Galindo and Chávez [10]; Hernández et al. [11]). In particular, in the northeastern state of Tamaulipas, with an extension of 80 174.68 km^2, comparable to that of Belgium and Holland together but with a 10 times lower population density (40.73 inhab km^{-2} on 2010) [Mexico's National Institute of Statistics and Geography, INEGI, http://www.inegi.org.mx/], a mean

* Corresponding author. Tel.: +52 646 1750500x24319.
E-mail address: drivas@cicese.mx (D. Rivas).

0960-1481/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.renene.2013.05.022

irradiation around 4.5 kW h m^{-2} d^{-1} has been estimated (Galindo and Chávez [10]; Hernández et al. [11]) and because of that it has been pointed as a promising region to establish photovoltaic farms (SENER [3]). However, Tamaulipas presents an uneven topography (see Fig. 1), with extensive coastal plains near the Gulf of Mexico, a rising cordillera running by north–south at its center and an extended highland in the western side. Tamaulipas State also presents a variety of climate regions (see Fig. 2). Based on the Köppen-Geiger climate classification (*e.g.*, Peel et al. [12]), it ranges from mostly temperate with no dry season and hot summers (Cfa) in the northern portion, mostly temperate with dry winters (Cw) in the central and southeastern portions, and tropical savannah (Aw) in the southern point; some locations in the central portions present a climate of arid hot steppe (BSh).

Therefore, as a first step in obtaining a more accurate estimate of the photovoltaic potential in Tamaulipas, it is of interest to estimate the incident solar energy, but given the very limited records of solar radiation in the study area, here we propose an empirical model to estimate the solar energy from other climatic information available, and the estimates are objectively mapped to cover most of the area. Previous studies have reported solar-radiation climatologies that include our study area (Galindo and Chávez [10]; Galindo Estrada and Cifuentes Nava [13]; Hernández et al. [11]), but with less detail and lower resolution, given their very limited data set. The purpose of this paper is to present a climatology of incident solar energy in Tamaulipas State, northeastern Mexico, which can be useful for the estimation of the photovoltaic potential in this region.

The rest of the paper is organized as follows: Section 2 describes the data used in this analysis and its processing, as well as the formulation of an empirical model to estimate the climatological incident solar energy as function of other climatic variables, which is complemented with an objective mapping to obtain continuous solar-energy maps. In Section 3 the results of the analysis are shown, in particular for mean diurnal and seasonal evolutions of the solar energy, and ultimately the maps of estimated incident solar energy in Tamaulipas State. In Section 4, the implications of the climatologies of solar energy are discussed. Section 5 summarizes the main results.

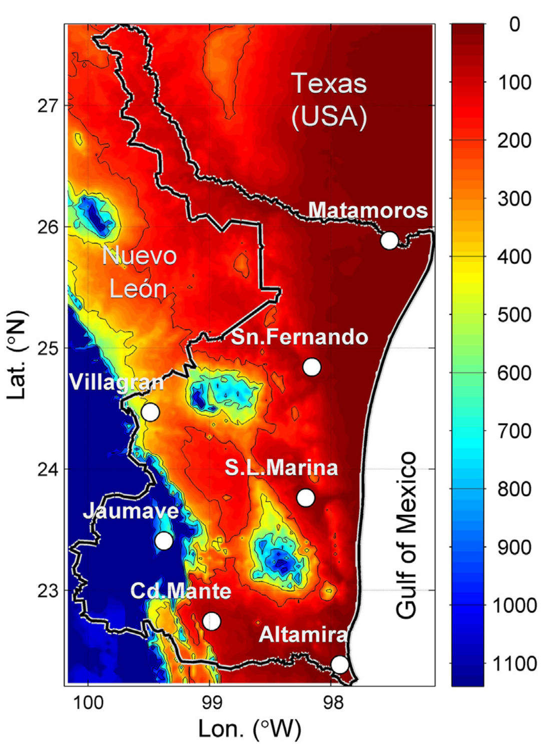

Fig. 1. Location of the 7 automatic meteorological stations in Tamaulipas State analyzed in this study. Color bar indicates the topography (in m), from the ETOPO2 (Smith and Sandwell [20]) gridded data set at 2′ resolution.

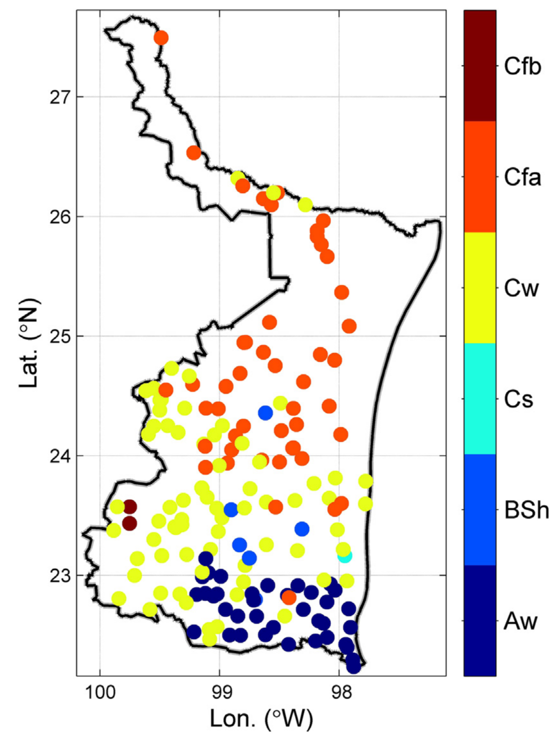

Fig. 2. Köppen-Geiger climate classification in the climatological conventional stations located along Tamaulipas State (see text). Aw: Tropical savannah; BSh: Arid hot steppe; Cs: Temperate with dry summer; Cw: Temperate with dry winter; Cfa: Temperate without dry season with hot summer; Cfb: Temperate without dry season with warm summer.

2. Data and methods

2.1. Data processing

Data from 7 automatic meteorological stations distributed along Tamaulipas State, held by the Mexico's National Commission of Water (CNA, by its acronym in Spanish), are used in this study (Fig. 1; Table 1). Such stations recorded several environmental variables (temperature, humidity, pressure, wind, precipitation, and solar radiation) every 10 min during different periods each, from year 1999 to year 2011. Fig. 3 shows the raw series of solar radiation, which are the focus in this study. The lack of continuous records is evident, only Altamira station has more than ten years, whereas Ciudad Mante station barely counts one year. Hourly data of solar radiation were calculated. The mean diurnal cycles

Table 1
Coordinates of the 7 meteorological stations shown in Fig. 1.

Station	Latitude (°N)	Longitude (°W)	Altitude (m)
Altamira	22°23′15″	97°55′32″	9
Ciudad Mante	22°44′40″	98°58′59″	85
Jaumave	23°24′27″	99°22′31″	750
Matamoros	25°53′09″	97°31′07″	4
San Fernando	24°50′34″	98°09′27″	45
Villagrán	24°28′14″	99°29′29″	390
Soto La Marina	23°45′51″	98°12′28″	21