Renewable Energy 81 (2015) 534–542

Contents lists available at ScienceDirect

Renewable Energy

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

Solar energy potential in the coastal zone of the Gulf of Mexico

Eunice Villicaña-Ortiz [a], Antonio J. Gutiérrez-Trashorras [b,*], José Pablo Paredes-Sánchez [b], Jorge Xiberta-Bernat [b]

[a] Departamento de Energías Renovables, Universidad Tecnológica del Centro de Veracruz, Av.Universidad, 350, Carretera Federal Cuitláhuac-La Tinaja, Congregación Dos Caminos, Cuitláhuac, 94910 Veracruz, Mexico

[b] Departamento de Energía, Escuela Técnica Superior de Ingenieros de Minas, Universidad de Oviedo, C/Independencia, 13, 2[a] Planta, 33004 Oviedo, Spain

ARTICLE INFO

Article history:
Received 18 March 2014
Accepted 24 March 2015
Available online 9 April 2015

Keywords:
Renewable
Solar technologies
Solar energy
Mexico

ABSTRACT

Mexico is an oil-producing country which has both fossil and renewable resources. The Gulf of Mexico is its primary source of conventional resources. The economic and environmental uncertainties arising from the widespread use of hydrocarbons, oil and natural gas make it necessary to develop indigenous renewable sources to promote the transition to a diversified energy mix, thus achieving a more sustainable energy model. Solar resources are important because of the high radiation levels throughout the country. Although use of solar power is conditioned by the climatic and meteorological characteristics of the area, it is likely to be applied in both electrical and thermal systems.

The coastal region of the Gulf of Mexico is characterized by a warm, humid climate and rugged terrain, with elevations over 1000 m. These conditions mean that in the central and southern areas, solar radiation is mainly diffuse. However, studies indicate that in spring and summer global irradiation can reach 4 kWh/m^2 day in the central and southern regions, and ascend to 6.7 kWh/m^2 day in the northwest. These levels are suitable for the development of solar photovoltaic energy and low temperature thermal installations, since the degree of cloud cover in these zones complicates the use of Concentrated Solar Power technology.

1. Introduction

Solar energy, and more specifically Concentrated Solar Power (CSP), is considered as one of the most promising options for future energy development, as its reduced cost and relatively low environmental impact makes it suitable to contribute to the global energy demand with wide applications in industry.

Mekhilef et al. study the solar energy systems utilization in industrial applications and looked into the industrial applications which are more compatible to be integrated with solar energy systems [1]. Du et al. characterize the solar energy literature from 1992 to 2011 using bibliometric techniques based on databases of the Science Citation Index and the Social Science Citation Index [2]. Solangi et al. discuss a review about the different solar energy policies implemented on the different countries of the world [3].

The growth of the world economy has been favored by the continued increase in the consumption of non-renewable energy sources in recent decades, particularly oil and gas. However, it should be noted that the current energy model does not allow a sustained and sustainable growth for many countries, due to imbalances between energy supply and energy demand, volatility of prices and the increasing concentration of greenhouse gases (GHG) (emissions from the use of fossil fuels).

The intensive use of fossil fuels in the energy sector in Mexico has caused a large increase in GHG emissions. The energy sector (production, processing, transportation and consumption of energy products) is the main source of these emissions (498.51 Mt CO_2 eq. in 2011 [4]). Achieving a lower level of energy dependence and mitigating emissions have led many researchers to the field of renewable energy sources. These studies highlight the importance of the role of renewable energy resources in the energy mix [5–8].

Mexico is an oil producing country and consequently the national energy model is based on the use of hydrocarbons. In fact, over 76% of the installed electricity production capacity comes from traditional power plants. Combined cycle plants have become especially important due to the improvements in their operation and the replacement of fuel oil by natural gas [4]. Forecasts of the Mexican Ministry of Energy (SENER) indicate predominant demand

* Corresponding author. Tel.: +34 985 10 43 27; fax: +34 985 10 43 22.
E-mail address: gutierrezantonio@uniovi.es (A.J. Gutiérrez-Trashorras).

http://dx.doi.org/10.1016/j.renene.2015.03.068
0960-1481/

for natural gas in the generation fleet by 2025. This means that renewable energies have had a limited development in Mexico, despite the interest in the late twentieth century.

This scenario suggests a major change in the structure of the energy model. It must be considered a priority, aimed at improving the chain of generation, transmission, distribution and the final use of energy. The economic and political uncertainties arising from the widespread use of oil combined with the increasing development of renewable energy resources worldwide have renewed interest in the use of the latter [9,10].

In Mexico there are alternatives that ensure an affordable and environmentally acceptable future energy supply. In order to cover the energy requirements of the country, these alternatives should be developed rationally and systematically, in the short and mid-term. Studies [11–14] indicate that Mexico boasts an interesting variety of renewable resources, capable of being transformed into final energy.

Of these, solar radiation is of particular importance because of its availability in nearly the whole national territory. It is estimated that average solar radiation rate is 5 kWh/m^{2}day over 75% of the territory, reaching 7 kWh/m^{2}day in the region near the Cortés Sea and Gulf of California. Even in the coastal zone of the Gulf of Mexico the solar radiation rate averages 4 kWh/m^{2}day, a much higher value than the 2 kWh/m^{2}day or 3 kWh/m^{2}day registered in the reference countries in the sector such as Germany and Spain [15–17]. The topography of the Gulf of Mexico favors the development of both electric and solar thermal installations, in addition to concentrating the main oil resources. The outline of a sustainable energy plan would combine the use of fossil and renewable resources for both domestic consumption and foreign trade.

This paper presents an analysis of the incident solar radiation on the coastal zone of the Gulf of Mexico, which includes the states of Tamaulipas, Veracruz, Tabasco and Campeche, in order to determine the available potential for its use as an energy source. This analysis reflects the need to establish guidelines for solar energy development and operation, contributing to the implementation of a more diversified energy model to meet the future energy demand in a sustainable way.

The analysis presented in this study is based on the use of a physical solar radiance model developed by Bird and Hulstrom [18]. This model allows to characterize and quantify the solar energy incident on a horizontal surface.

In Mexico, although there are some studies on the matter done by academic institutions [19–21], the influence of physical and meteorological factors on solar radiation are not related in them, so this is a study of special interest due to restricted development of this energy source despite the fact of its wide availability.

Solar availability is determined by the cloud cover rates for the area. In addition, radiation maps are a major step towards the development of solar systems for both thermal and electrical applications.

2. Analysis geographical and temporal availability of solar energy

2.1. Theoretical foundations

The Sun emits energy as electromagnetic radiation which travels from the solar core and is distributed uniformly and isotropically throughout the universe. Part of this energy reaches the upper layers of the Earth's atmosphere. Its value is known as the Solar constant (C), depending on the day of the year [22]. The atmosphere is made up of different molecules (H_2O, O_2, O_3, CO_2, etc.) and solid particles of different sizes known as aerosols (dust, soot, pollen, etc.). When radiation passes through the atmosphere it undergoes variations, giving rise to scattering, absorption and reflection [23]. These phenomena can reduce the power of the incident radiation by as much as 50%, giving rise to local and seasonal variations [24].

The analysis of these phenomena quantifies and characterizes solar resources. The study is performed by using techniques such as the logging of measurements, the treatment of satellite images and the use of physical models of irradiation. The first technique involves the use of costly specific measurement instruments. The second technique gives better results because it can evaluate the presence of shaded areas, but its use is also limited because of its high cost. The logical alternative is the use of physical and mathematical models based on the use of meteorological data. This technique for the analysis of radiation is an affordable tool which obtains rigorous results.

2.2. Solar irradiance physical model

The use of physical models of irradiance may have limited results if the appropriate data and model are not employed. In this case, the Bird and Hulstrom model is used as a base since it considers the elements that attenuate solar radiation passing through the atmosphere. Specifically, it has been used the non spectral Bird and Hulstrom model, also known as model "C" of Iqbal [23,25]. This model identifies the set of coefficients responsible for the attenuation due to the presence of different particles present in the Earth's atmosphere.

It is important to highlight that some equations were improved and complemented using correlations made by Mächler, and also using tabulated values, such as monthly changes in atmospheric ozone under normal conditions of pressure and temperature, in order to evaluate more accurately the atmospheric components [23].

This model determines the total irradiance (I_{TH}), from the amount of direct radiation (I_{DH}) and diffuse irradiance (I_{dH}) on a horizontal surface for the entire frequency band [25], according to Equation (1).

$$I_{TH} = I_{DH} + I_{dH} \tag{1}$$

2.2.1. Solar direct irradiance

The direct irradiance on a horizontal surface is determined from Equation (2), assuming a clear sky, free of clouds.

$$I_{DH} = 0.9662 \cdot C_r \cdot \tau_r \cdot \tau_o \cdot \tau_g \cdot \tau_w \cdot \tau_a \cdot \cos\theta \tag{2}$$

being:

C_r: Value of daily solar constant (W/m^2).
τ_r: Transmission coefficient by scattering due to air molecules.
τ_o: Transmission coefficient due to absorption of ozone (O_3).
τ_g: Transmission coefficient due to absorption by the uniform gases mixture (CO_2 and O_2).
τ_w: Transmission coefficient due to absorption of water vapor.
τ_a: Transmission coefficient due to absorption and scattering by the presence of aerosols.
0.9662: Correction factor which adjusts the wavelength range which accounts for 96% of radiation.
θ: Solar Zenith Angle

Equation (2) groups all responsible coefficients for the attenuation of the radiation, which gives more consistent values of direct radiation.

The normalized solar constant varies around ±3.5% over the year due to the eccentricity of the elliptical path of the Earth around the