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

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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

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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$_2$O, 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

Sun. Therefore, for the development of projects of this type of energy, it is needed to determine its daily value. The latter is determined multiplying the normalized solar constant ($C = 1367$ W/m^2), by the relationship between the average Earth-Sun distance and the actual distance at a given day (Julian day), as shown in Equation (3) [23].

$$C_r = C \cdot \left(1 + 0.033 \cdot \cos \frac{360 \cdot n}{365}\right) \tag{3}$$

where n is the Julian day.

The density of a substance multiplied by the path length is called optical substance mass. The optical air mass value should be previously determined (m_a) in order to obtain the transmission coefficients due to scattering by air molecules and due to absorption by uniform mixing of these miscible gases. The optical air mass is a function of the pressure and the relative air mass (m_{rel}). The latter is a purely geometrical relation that evaluates the intersection of a solar beam with the atmosphere, considering the curvature of the earth.

In this model, the value of the transmission coefficient by scattering evaluates the change of direction experienced by the solar radiation due to the presence of air molecules and it is determined using Equation (4).

$$\tau_r = e^{-0.0903 \cdot m_a^{0.84}\left(1 + m_a - m_a^{1.01}\right)} \tag{4}$$

For this calculation the optical air mass value (m_a) has to be determined. It is corrected by the pressure value as suggested by the Atwater y Ball model (Equation (5)) [23].

$$m_a = \frac{P_T \cdot m_{rel}}{101325} \tag{5}$$

In this equation P_T is the total air pressure expressed in Pa. It is determined as a function of the altitude (z) by means of the Equation (6).

$$P_T = 101325 \cdot e^{-0.0001184z} \tag{6}$$

In order to calculate the air mass value, it is necessary to evaluate the relative air mass (m_{rel}) (Equation (7)).

$$m_{rel} = \frac{1}{Cos\theta + 0.15[93.885 - (\theta)]^{-1.253}} \tag{7}$$

The relative air mass reaches its minimum value when the solar incidence is normal to the Earth's surface ($\theta = 0°$). The equation also indicates that the length of the solar radiation path decreases very quickly as the zenital angle (θ) diminishes.

In order to calculate the transmission coefficient due to the absorption of ozone (τ_o) the thickness of the layer corresponding to the ozone atmosphere (Lo) of Mexico is needed. For the case studied, this value was taken from the tabulated values by Iqbal, for which the thickness depends on the latitude and time of year [19].

According to Bird y Hulstrom model, τ_o is obtained by the Equation (8).

$$\tau_o = 1 - \left[0.1611 \cdot \left[(Lo \cdot m_{rel})(1 + 139.48 \cdot Lo \cdot m_{rel})^{-0.3035}\right] \right.$$
$$\left. + \frac{0.002715 \cdot Lo \cdot m_{rel}}{1 + 0.044 \cdot Lo \cdot m_{rel} + 0.003 \cdot (Lo \cdot m_{rel})^2}\right] \tag{8}$$

Besides ozone there are other gasses in the Earth's atmosphere absorbing radiation such as CO_2 and O_2. To determine the transmission coefficient due to absorption by the uniform gases mixture (τ_g) Equation (9) is used [23].

$$\tau_g = e^{-0.0127 \cdot m_a^{0.26}} \tag{9}$$

The steam contained in the atmosphere is one of the elements with the highest capacity for radiation absorption. The transmission coefficient due to absorption of water vapor (τ_w) is obtained from Equation (10) [23].

$$\tau_w = 1 - \frac{2.4959 \cdot (U_w)}{(1 + 79.034 \cdot U_w)^{0.6828} + 6.385 \cdot U_w} \tag{10}$$

This coefficient depends on the steam optical path (U_w), which is determined from amount of water capable of precipitate in the vertical direction over the place (WW) multiply by relative air mass (m_{rel}) (Equation (11)).

$$U_w = WW \cdot m_{rel} \tag{11}$$

In order to calculate the amount of water capable of precipitate in the vertical direction over the place, measurement equipments called radiosondes are used. If these equipments are not available, it could be used use the expression proposed by Leckner (Equation (12)) [26]. In this study this equation has been used.

$$WW = 0.493 \left(\frac{HR}{T}\right) e^{26.23 - 5416/T} \tag{12}$$

being:

T: Absolute temperature
RH: relative humidity

Mächler parameterization [27] is used for the transmission coefficient due to the presence of aerosols (τ_a), according to the Iqbal model (Equation (13)). This parameterization depends on the average particle size (α) and the amount of aerosols. According to various studies [23,28,29], the average particle size is 1.3μm ± 0.2. The amount of aerosols is measured by the turbidity degree of the atmosphere (β). This parameter is called the Angstrom turbidity coefficient and it can vary from 0, for extremely clean atmospheres, up to 0.5, for atmospheres with extremely high turbidity.

$$\tau_a = 0.12445 \cdot \alpha - 0.0162$$
$$+ (1.003 - 0.125 \cdot \alpha) \cdot e^{-\beta \cdot m_a(1.089 \cdot \alpha + 0.5123)} \tag{13}$$

2.2.2. Solar diffuse irradiance

With regards to diffuse irradiance, the model considers the contribution of three solar components: diffuse irradiance due to the existence of air molecules, diffuse irradiance due to the existence of dust particles (aerosols) and diffuse irradiance by multiple reflection between the ground and atmosphere [23] (Equation (3)).

$$I_{dH} = I_{dr} + I_{da} + I_{dm} \tag{14}$$

being:

I_{dH}: Total diffuse irradiance on a horizontal surface.
I_{dr}: Diffuse irradiance due to scattering by air molecules (Rayleigh diffusion).
I_{da}: Diffuse irradiance due to the presence of aerosols.
I_{dm}: Diffuse irradiance due to multiple reflections.

Diffuse irradiance due to the existence of air molecules (I_{dr}) is determined by means of the Equation (15).

$$I_{dr} = 0.79 \cdot C_r \cdot \tau_o \cdot \tau_g \cdot \tau_w \cdot \tau_{aa} \cdot 0.5 \cdot \frac{1 - \tau_r}{1 - m_a + m_a^{1.02}} \cdot \cos\theta \qquad (15)$$

This model assumes that 50% of the solar energy is directed toward the Earth's surface due to scattering by air molecules. The transmission coefficient due to absorption by aerosols (τ_{aa}) requires an albedo (ratio of reflected radiation from the surface to incident radiation upon it) called a single scattering albedo (ω_o). The value suggested by the Bird and Hulstrom model is 0.9 [18]. The transmission coefficient due to absorption by aerosols is obtained by the Equation (16).

$$\tau_{aa} = 1 - (1 - \omega_o)\left(1 - m_a + m_a^{1.06}\right)(1 - \tau_a) \qquad (16)$$

The diffuse radiation due to the presence of aerosols (I_{da}) is calculated by means of Iqbal's C Model, in which the percentage of energy reaching the earth's surface due to scattering from aerosols is obtained using Mac's parameterization [27] (Equation (17)).

$$I_{da} = 0.79 \cdot C_r \cdot \tau_o \cdot \tau_g \cdot \tau_w \cdot \tau_{aa} \cdot F_c \cdot \frac{1 - \tau_{as}}{1 - m_a + m_a^{1.02}} \cdot \cos\theta \qquad (17)$$

where F_c represents the percentage of the energy on the Earth's surface due to scattering by aerosols. In ca be estimated from the expression provided by the Mac's model (Equation (18)).

$$F_c = 0.93 - 0.21 \ln m_a \qquad (18)$$

and τ_{as} represents the transmission coefficient due solely to diffusion by aerosols which is obtained from Equation (19).

$$\tau_{as} = \frac{\tau_a}{\tau_{aa}} \qquad (19)$$

The calculation of the diffuse irradiance by multiple reflections (I_{dm}) requires the reflection coefficients of the surface (ρ_g), which are tabulated depending on the surface. It also requires an evaluation of the atmospheric albedo, ie, multiple reflections between the ground and the sky (ρ_α') [29] (Equations (20) and (21)).

$$I_{dm} = (I_{DH} \cdot \cos\theta + I_{dr} + I_{da}) \frac{\rho_g \cdot \rho_\alpha'}{1 - \rho_g \cdot \rho_\alpha'} \qquad (20)$$

$$\rho_a' = 0.0685 + (1 - F_c)(1 - \tau_{as}) \qquad (21)$$

As can be seen, the application of the Bird and Hulstrom model assesses the influence of climatic and meteorological variables, which are responsible for the attenuation of solar radiation, giving very reliable results.

2.3. Application to the coastal area of the Gulf of Mexico

Application of the model was performed for the coastal zone of the Gulf of Mexico, which includes the states of Tamaulipas, Veracruz, Tabasco and Campeche (Fig. 1). Solar resource analysis began with the calculation of the coefficients of atmospheric transmission given by Bird and Hulstrom model. To do so, the climate information provided by the meteorological stations located in different areas of the coastal region was used. This region is characterized by plains that do not exceed 1000 m in altitude with the exception of some interior areas with higher altitudes. It has a variety of climates ranging from warm to temperate, with different moisture contents. However, humid and sub-humid warm climates are predominant.

To evaluate the incident solar energy it is necessary to use climate data available in existing weather stations in the area [30] (Table 1).

These stations are part of the National Weather System [26]. The recorded variables are: the relative humidity (RH), precipitation (mm), temperature (°C), pressure (bar), altitude (meters above sea level: masl), and number of rainy days, foggy days, sunny days and clear days. Climate records take an average of 20 years to accumulate sufficient data to establish standard year statistics. This information is used to obtain the data matrix of the 10 weather stations in the study area (Fig. 2).

Once the working equations have been established, the direct and diffuse solar radiation for each of the weather stations are is assessed. In this region, three atmospheric states (clear, cloudy and very turbid) have been identified according to the Angstrom turbidity coefficient. The parameter values are [31]:

- β = 0.10 when the atmosphere is clear. This indicates a blue, cloud-free sky that occurs only on certain occasions.
- β = 0.20 when the atmospheric conditions have slight cloudiness. This feature is more common. Some authors identify it as a clear blue sky, with a bit of haze.
- β = 0.40 when the atmosphere has a very cloudy appearance. In this case, the sky has a "milky" color typical of extreme haze.

The daylight hours available for each site must be evaluated in order to obtain daily direct and diffuse radiation. Values given by the Mexican government were used [32].

3. Discussion of results

The availability of solar energy is conditioned by several climatic and meteorological factors. For the analysis of solar radiation information it is necessary to know the final application of the solar resources. If the final use is energetic, it is necessary to determine the availability of the resources more accurately. Therefore, the fact that the irradiation model used in this analysis considers the atmospheric state is decisive.

3.1. Radiation type

Table 2 shows the daily solar radiation values for the three atmospheric states in each weather station. The highest overall level of daily solar radiation is obtained in Cuidad Victoria in particle-free atmospheric conditions. However, this condition is unusual because of the physical conditions and weather in the area.

Of these radiation levels, it is important to distinguish between the fraction corresponding to the direct radiation and that which corresponds to diffuse radiation, as this will determine the most

Fig. 1. Location of the coastal zone of the Gulf of Mexico.

Table 1
Meteorological data from weather stations in the Gulf of Mexico.

Station	State	Latitude	Longitude	Altitude (masl)	Temperature (°C)	RH (%)
Coatzacoalcos	Veracruz	18°11′22″	94°30′39″	16	26	0.78
Villahermosa	Tabasco	17°59′	92°56′	7	25	0.75
Jalapa	Veracruz	19°30′43″	96°54′14″	1360	19	0.46
Ciudad Victoria	Tamaulipas	23°44′52″	99°10′18″	336	25	0.71
Tampico	Tamaulipas	22°12′	97°51′22″	25	25	0.78
Soto la Marina	Tamaulipas	23°46′	98°12′	21	26	0.65
Veracruz	Veracruz	19°09′40″	96°08′13″	20	25	0.78
Tuxpan	Veracruz	20°57′35″	97°25′08″	10	25	0.82
Campeche	Campeche	19°50′	90°30′	5	27	0.72
Orizaba	Veracruz	18°51′	97°06′	1259	18	0.78

suitable type of technology to develop: solar thermal for low or medium temperature, isolated photovoltaic, or grid-connected photovoltaic. Because the goal of this analysis is to determine the level of radiation that can be harnessed, a very turbid atmosphere was used to establish the minimum solar daily solar radiation in the worst situation. The obtained results are shown in Table 3.

Radiation levels, even in very turbid atmospheric conditions, are interesting for the development of solar systems. Fig. 3 shows the behavior of the level of radiation throughout the year for all the weather stations.

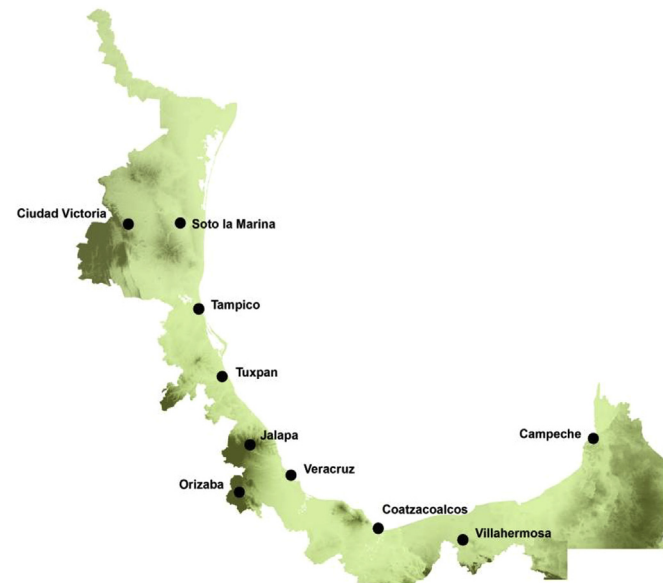Fig. 3 also shows that the monthly average total solar radiation is considerably higher in the region of Ciudad Victoria. Orizaba and Jalapa have virtually identical radiation conditions throughout the year, receiving the lowest irradiation. Stations located in the areas nearest to the sea share similar trends; Campeche and Veracruz have the same level of radiation.

In a second analysis the level of radiation received on a seasonal basis was measured in order to identify the highest values of solar radiation obtainable in very turbid atmospheric conditions. For all the stations it was observed that solar resources are higher in spring and summer than in winter and autumn. This analysis also indicates the energy contribution given by the direct and diffuse radiation in each season (Fig. 4).

Fig. 4 shows that the maximum radiation occurs in Victoria, reaching the greatest amount of direct radiation in spring and summer. The Soto la Marina station also has significant direct radiation values. In contrast, Jalapa and Orizaba have the lowest average solar resources.

3.2. Development potential

As it was mentioned before, according to final energy use (thermal or electrical) the type and amount of solar radiation in the area under study have to be considered. Thus, for the development

Fig. 2. Location of the weather stations of the Coastal Zone of the Gulf of Mexico.

Table 3
Total, direct and diffuse annual average daily solar radiation for the different weather stations.

Stations	Daily solar radiation [kWh/m²day]		
	Total	Direct	Diffuse
Ciudad Victoria	5.895	3.184	2.711
Soto la Marina	5.020	2.711	2.309
Tampico	4.439	2.413	2.026
Tuxpan	4.138	2.261	1.877
Jalapa	3.568	1.959	1.608
Orizaba	3.506	1.930	1.576
Veracruz	4.936	2.715	2.222
Coatzacoalcos	4.750	2.620	2.130
Villahermosa	4.401	2.429	1.972
Campeche	4.893	2.685	2.209

Table 2
Overall average daily solar radiation at the weather stations according to the atmospheric states.

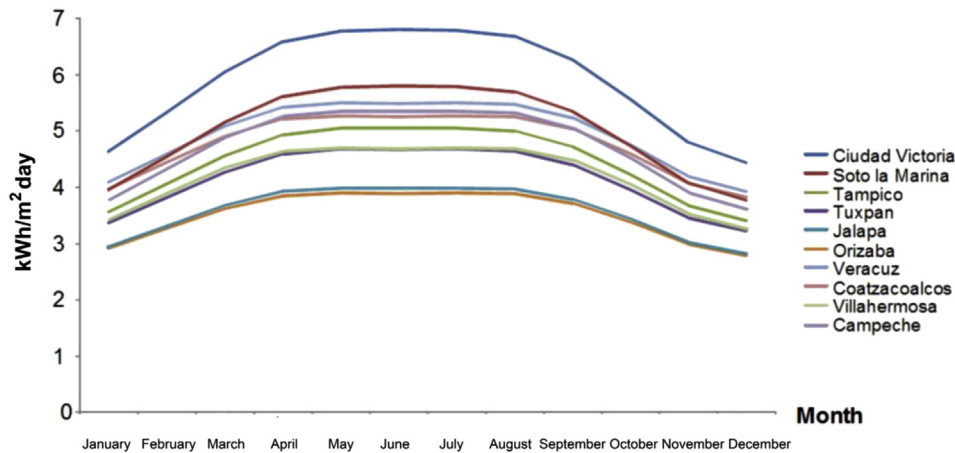| Stations	Clear atmosphere [kWh/m²day]	Cloudiness atmosphere [kWh/m²day]	Very turbid atmosphere [kWh/m²day]
Ciudad Victoria	6.729	6.183	5.895
Soto la Marina	5.731	5.265	5.020
Tampico	5.065	4.655	4.439
Tuxpan	4.720	4.339	4.138
Jalapa	4.068	3.741	3.568
Orizaba	3.997	3.676	3.506
Veracruz	5.629	5.176	4.936
Coatzacoalcos	5.416	4.980	4.750
Villahermosa	5.017	4.614	4.401
Campeche	5.581	5.131	4.893

Fig. 3. Monthly average total daily solar radiation at the weather stations.

of solar photovoltaic isolated type, daily solar radiation level between 3 and 4 kWh/m^{2}day is required. Regarding solar installations connected to the grid, in addition to greater insolation (sunshine hours) and localizations free of shadows, a level of more than 4 kWh/m^{2}día daily solar radiation is required. It should be noted that in areas where diffuse radiation predominates, it must not be carried out photovoltaic systems, since the electricity production will be very low. Therefore, locations with significant cloud cover throughout the year are not suitable for the development of solar photovoltaic grid-connected installations.

In order to produce thermal energy for sanitary hot water, the daily solar radiation levels required are between 2.5 and 3 kWh/m^{2}day. For thermal systems of medium and high temperature, ie concentrated solar power (CSP), the production of heat and electricity requires direct irradiation, as well as a significant level of solar radiation. Thus, regions with values greater than 5 kWh/m^{2}day are optimal for the development of Concentrated Solar Power installations. According to the study conducted by Greenpeace and the European Association of Solar Energy [33], areas where Concentrated Solar Power systems can be successfully developed are those with more than 5.4 kWh/m^{2}day. It also suggests areas with low humidity and low levels of dust or smoke (aerosols), particularly steppes, scrublands, savannas and deserts below 40° latitude.

Solar radiation maps have been elaborated with the help of the ArcGis tool to identify regions of interest for solar energy use.

3.2.1. Direct radiation

Fig. 5 displays the direct radiation of the Gulf of Mexico solar map. The highest level of estimated direct radiation reaches 3.9 kWh/m^{2}day.

From the analysis, it appears that the coastal zone of the Gulf of Mexico has levels of interest for the development of solar thermal systems of different radiation types, even when considering very turbid atmospheric conditions.

The results obtained indicate that technologies such as CSP would not be profitable because of the percentage of cloud cover. However, this region is suitable for the development of either isolated or grid-connected photovoltaic systems.

For grid-connected systems, the areas with the greatest potential are those located northwest of the state of Tamaulipas and virtually the entire state of Campeche. Central Veracruz is not advisable due to the degree of cloudiness, although its development may be feasible.

3.2.2. Diffuse radiation

Fig. 6 shows that the highest values of diffuse solar radiation are mainly achieved in the central zone, comprising the states of Tamaulipas and Veracruz, where the level of diffuse radiation is approximately 2.8 kWh/m^{2}day.

From the analysis, it appears that this region offers possibilities for the development of isolated photovoltaic systems, and virtually the entire region is recommended in the use of low temperature solar thermal systems for hot water and pool heating.

3.2.3. Total radiation

Fig. 7 indicates that this region can reach a level of global radiation up to 6.7 kWh/m^{2}day, the Northwest being the largest energy resource zone. For the central zone, the levels are lower, in the range of 3 kWh/m^{2}day and predominantly due to the diffuse radiation contribution. In the south, radiation also presents values near 4 kWh/m^{2}day, providing opportunities for the development of solar systems for energy purposes.

4. Conclusions

Solar resources can contribute to the development of a sustainable energy model using renewable energy. Availability depends on the climatic characteristics of each zone. Climatic and meteorological factors determine the degree of attenuation of solar radiation and, therefore, the amount of available solar resources.

Solar direct, diffuse and total radiation maps of the coastal zone of the Gulf of Mexico have been elaborated in order to identify regions of interest for solar energy use.

Solar energy is an abundant resource in the Gulf of Mexico, where it reaches 3.9 kWh/m^{2}day of direct radiation, and 2.8 kWh/m^{2}day of diffuse radiation. The total radiation is up to 6.7 kWh/m^{2}day in the northwest, 3 kWh/m^{2}day in the center, where the main contribution is due to diffuse radiation, and about 4 kWh/m^{2}day in the south.

Radiation levels in the coastal zone of the Gulf of Mexico are suitable for the development of both photovoltaic and thermal solar power plants. Photovoltaic systems could be either isolated or grid-connected. The results indicate that technologies such as Concentrated Solar Power would not be profitable due to the percentage of cloud cover. For grid-connected systems, areas with the greatest potential are Tamaulipas and Campeche. The central area, Tamaulipas and Veracruz offer possibilities for the development of solar thermal applications with low temperature systems for hot water and pool heating. The development and use of these
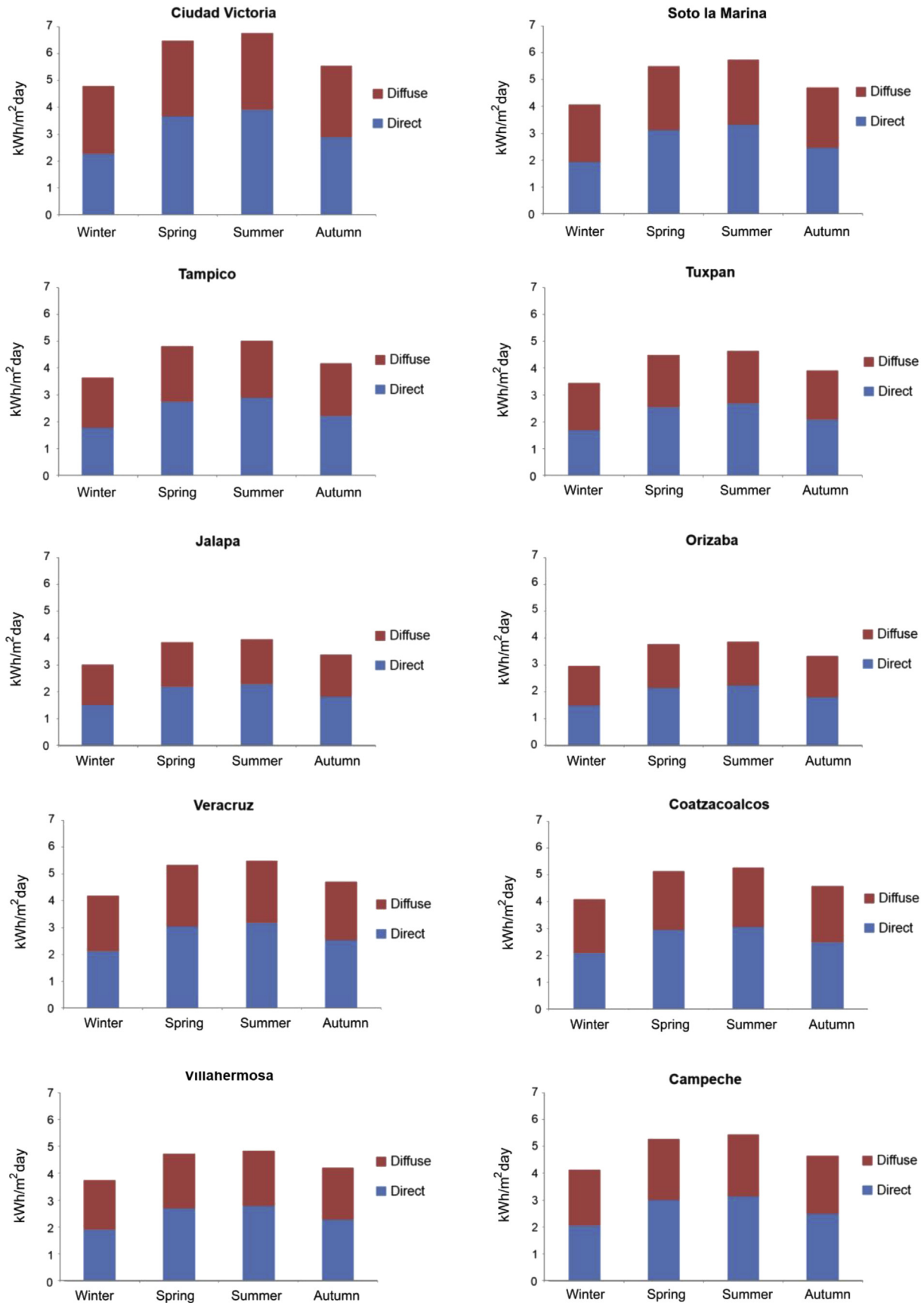
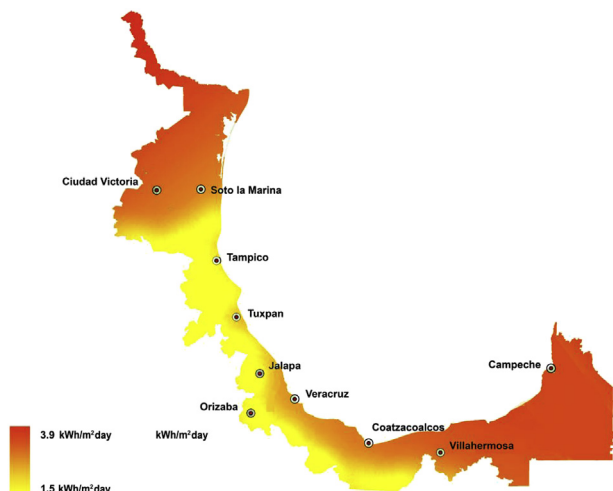**Fig. 4.** Direct and diffuse seasonal average daily solar radiation at weather stations.

resources requires support and incentives to achieve the structural improvements necessary for its use and integration in the productive energy system.
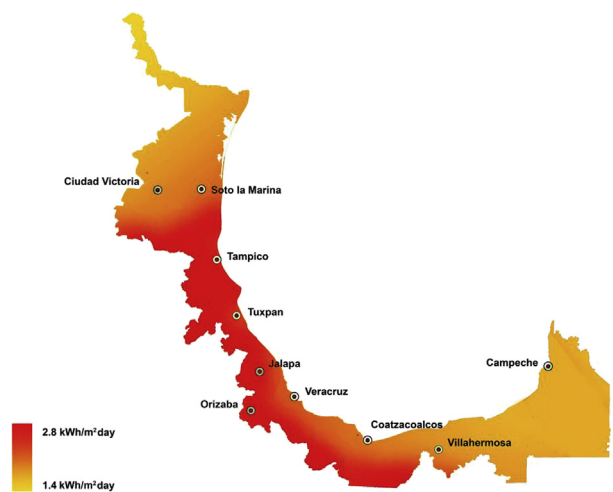

Fig. 5. Direct solar radiation in the coastal zone of the Gulf of Mexico.

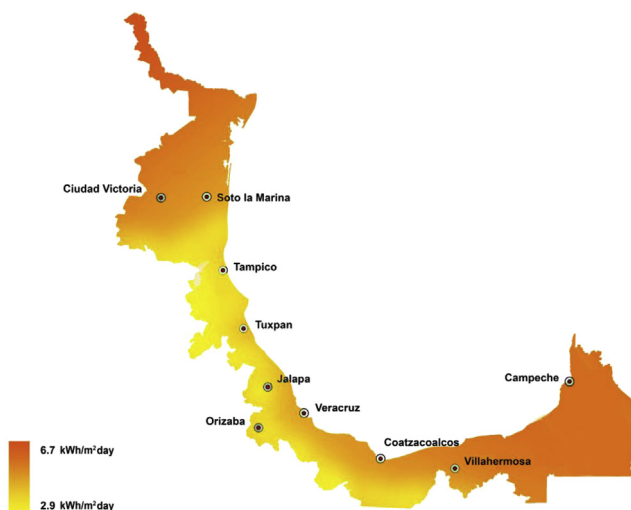**Fig. 6.** Diffuse solar radiation in the coastal zone of the Gulf of Mexico.

Fig. 7. Total solar radiation in the coastal zone of the Gulf of Mexico.

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