Global solar radiation, assessed using a pyranometer placed on an inclined plane

Radiación solar global, evaluada mediante un piranómetro colocado en un plano inclinado

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Abstract

The city of Zacatecas, due to its geographical location, a city with little industry, neighboring the Tropic of Cancer and a height of the order of 2,492 above sea level, has the conditions for a study of the behavior of solar radiation and its possible potential use to transform it into other types of energy. The objective of this work was to have an irradiance database in the city of Zacatecas using CMP 22 Kipp & Zonen pyranometers from Campbell scientific, in order to satisfy the needs derived from radiation-related industry activities. The pinanometers are located at the Zacatecas_04 Solarimetric Station, which is located on the UAZ Siglo XXL Campus in building 6 of the Academic Unit of Chemical Sciences of the Autonomous University of Zacatecas (Lat: 22°46'21.01"N, Long: 102°38'37.14") in the city of Zacatecas, Zac, and is part of the Mexican Solarimetric Network promoted by the Mexican Solarimetric Service of the Institute of Geophysics of the National Autonomous University of Mexico. The data was rearranged into hourly, daily and monthly averages. The average daily irradiance was 547 ± 5 W/m².

Pyranometer, Irradiance, Solar radiation

Resumen

La ciudad de Zacatecas por su ubicación geográfica, ciudad poco industrial, vecina al trópico de Cáncer y altura del orden de 2,492 sobre el nivel del mar, tiene condiciones para un estudio del comportamiento de la radiación solar y de su posible uso potencial para transformarlo en otros tipos de energía. El objetivo de este trabajo fue contar con una Base de Datos de la irradiancia en la ciudad de Zacatecas empleando piranómetros CMP 22 Kipp & Zonen de Campbell scientific, para poder satisfacer las necesidades derivadas de las actividades de la industria relacionadas con la radiación. Los pinanómetros están colocados en la Estación Solarimétrica Zacatecas_04 que se ubica en el Campus UAZ Siglo XXL en el edificio 6 de la Unidad Académica de Ciencias Químicas de la Universidad Autónoma de Zacatecas (Lat: 22°46’21.01’’N, Long: 102°38’37.14’’) en la ciudad de Zacatecas, Zac, y forma parte de la Red Solarimétrica Mexicana impulsada por el Servicio Solarimétrico Mexicano del Instituto de Geofísica de la Universidad Nacional Autónoma de México. Los datos se reacomodaron en promedios horarios, diarios y mensuales. La irradiancia promedio diario fue de 547 ± 5 W/m².

Piranómetro, Irradiancia, Radiación solar

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Introduction

Solar radiation does not require any intermediate material medium between the sun and the earth to be transported, so the energy released by the sun travels through the vacuum of space and reaches the earth directly in the form of waves that carry a certain amount of energy.

The earth's atmosphere is almost transparent to solar radiation but the surface of our planet and other bodies above it do absorb it, most of the radiation 51% is absorbed by the earth's surface.

As time goes by, human beings are very dependent on this energy, but with the increase in population, the energy demand is much higher, and thus the process of obtaining it becomes more complicated, for this reason it is necessary to use other alternatives that are profitable but at the same time do not harm the environment.

In 2014, SENER and CONACYT promoted the project to create the Mexican Center for Innovation in Solar Energy (CEMIESOL), which was in charge of the Institute of Renewable Energies of the UNAM. This allowed the installation of the first national reference solarimetric network. This network consists of 10 solarimetric stations distributed throughout the national territory, according to a regionalization carried out through a multivariate statistical analysis method (ISODATA method). These stations were located in research or higher education centers, which of course were interested in having solarimetric information to conduct research either as applied or as human resources training, such as the one of the Universidad Autónoma de Zacatecas.

The primary function of the Mexican Solarimetric Service is to generate accurate information of the largest number of sites in our country and the largest number of solar radiation components, through its network of solarimetric stations (Geofisica, 2019).

The Sun is a star that generates energy under a nuclear fusion process, through which hydrogen is converted into helium, as shown in Figure 1.

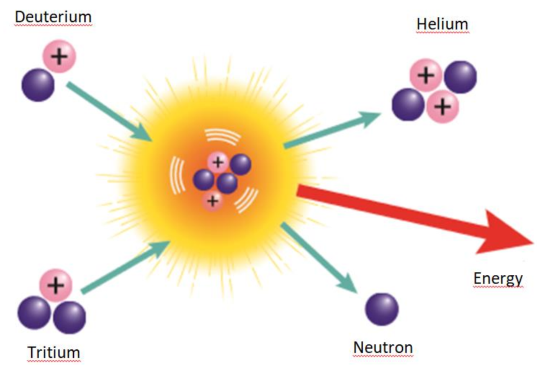

Figure 1 Nuclear fusion reaction in the Sun
Source: Thermal Applications of Solar Energy, p.22

The sun can be divided into core, convective-radiative zone and corona. In the core is where the fusion reaction happens, and the convective-radiative zone is where the transfer of energy to the corona occurs, which is the surface we observe from Earth (Figure 2), the temperatures inside the core exceed millions of kelvin, but it is estimated that on the surface of the Sun the average temperature is almost 5,778 K (García *et al*, 2017).

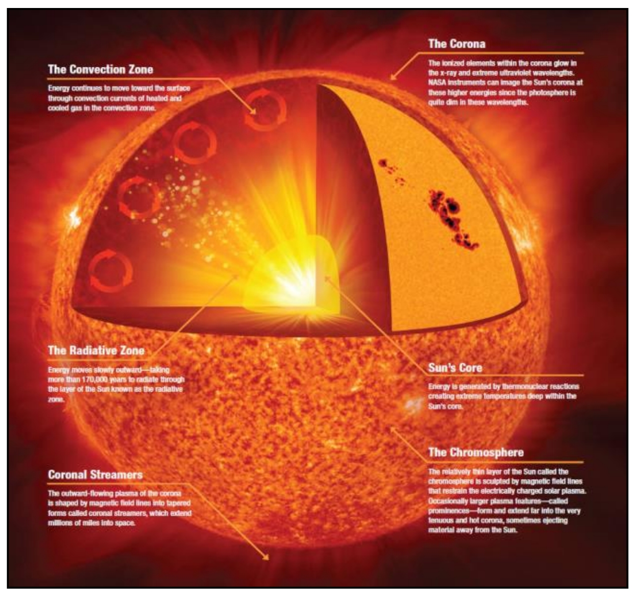

Figure 2 Structure of the Sun
Source: NASA, 2018

The amount of radiation per unit area that the Earth receives at the top of the atmosphere is almost a constant, it can vary slightly throughout the year because the Earth's orbit around the Sun is elliptical, so it presents approaches or distances from the star, and also because of solar activity whose cycle is 11 years.

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The updated and most accurate value is de $1{,}360.8 \pm 0.5 W/m^2$, this value is known in the engineering literature as the "solar constant" G_SC but it is known that it is not exactly a universal constant in the scientific sense and that these small variations can affect the terrestrial climate but are not very important in solar energy applications (García *et al.*, 2017).m The radiation emitted by the Sun's surface has a spectral distribution that resembles that of a blackbody at 5,772 K, as seen in Figure 3 (Garcia *et al.*, 2017).

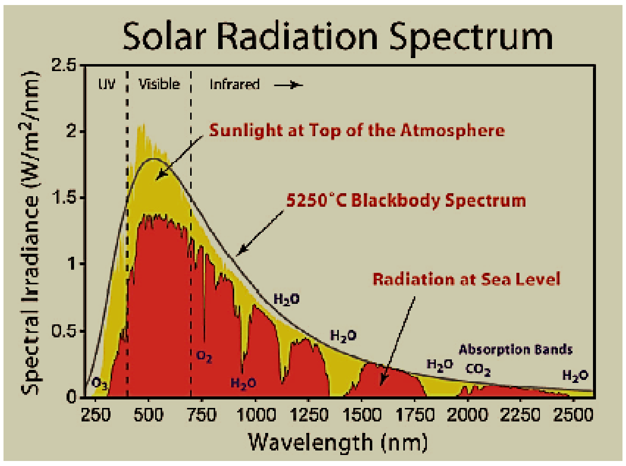

Figure 3 Solar spectrum at the top of the atmosphere and at sea level
Source: NASA image, 2018

Einstein posits that radiant energy is a stream of tiny packets of energy. Each packet of energy, called a photon, behaves like a small particle. Extending Planck's quantum theory, Einstein deduced that each photon should contain an energy proportional to the frequency of light, represented by equation 1 (Brown e*t al.*, 2004).

$$Photon\ energy = E = hv \qquad (1)$$

The Earth revolves around the Sun describing an elliptical orbit, the Sun is at one of the foci and the average Earth-Sun distance is approximately $149.46x10^6$ km (approx. $1.5x10^{11}$ m), this value is called Astronomical Unit, AU. The eccentricity of the Earth's orbit is 1.7%, where the smallest distance between the Sun and the Earth is at Perihelion, which generally occurs in January and is $R = UA(1-e) = 0.983UA = 147.5x10^6$ km; it occurs in the month of July when the distance between the Earth and the Sun is greatest, known as Aphelion and is $R = UA(1+e) = 1.017UA = 152.6x10^6$km.

One revolution around the Sun is one cycle year and is completed in 365 days, this motion is called translational (Benavides *et al*, 2017). Figure 4 shows the elliptical orbit of the Earth around the Sun.

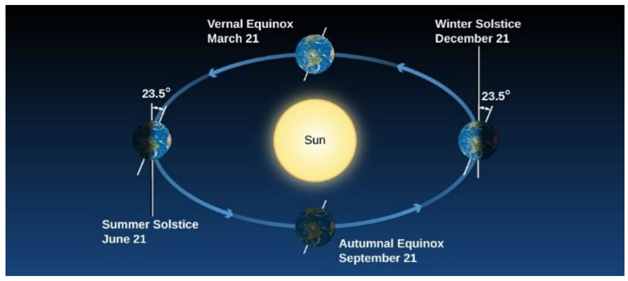

Figure 4 Earth's orbit throughout the year, seasons of the year considered in north pole
Source: (Atlas of solar, ultraviolet and ozone radiation of Colombia - Benavides, Simbaqueva and Zapata, 2017)

In turn, the Earth rotates around its own axis with an approximate duration of 24 hours, and this phenomenon is known as rotational motion causing day and night. The Earth's axis is slightly displaced (23°26'7") with respect to the plane of the orbit. This plane is called the ecliptic. The translational motion in conjunction with the Earth's obliquity produces the seasons of the year (Caballinas, 2017).

Due to the rotational motion the angle with which the sun's rays strike the Earth's surface varies between -23.5° with respect to the Equator, when it is the Winter Solstice (December 22) and +23.45° at the Summer Solstice (June 21), being the longest day Benavides *et al*, 2017), is represented in Figure 5.

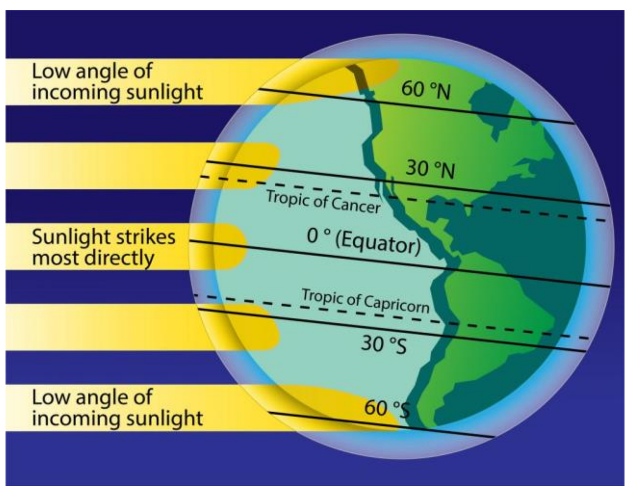

Figure 5 Variation of the direction of the sun's rays over the Earth's surface throughout the year
Source: (Thermal Applications of Solar Energy, p. 25)

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Most of the radiation 51% is absorbed by the Earth's surface, only 19% is absorbed directly by atmospheric components and clouds, while 30% is reflected by surface and atmospheric gases and particles and back to outer space.

The Earth's atmosphere is an inhomogeneous mixture of various gases and aerosols (solid particles or liquid droplets in suspension), they form a layer surrounding the Earth, the gases that compose it are mainly $O_3, O_2, N_{2,} CO_{2,},$ among others in very small quantities (Abal and Durañona, 2013).

There are several phenomena present during the path of electromagnetic radiation coming from the Sun through the atmosphere, such as the following: Scattering; The phenomenon that occurs when electromagnetic radiation interacts with particles or molecules of gases present in the atmosphere, and a part of it is redirected randomly without changing the wavelength (Rayleigh scattering). Absorption. It occurs when molecules of ozone (O_3), water vapor (H_2O) or carbon dioxide (CO_2) together with aerosols of dust particles, ice and other substances, receive solar radiation that increases their temperature.

This fraction of the total energy can be as high as 15%, depending on atmospheric conditions; and Reflection. The clouds made up of water and ice aerosols reflect a large amount of radiation initially, thus blocking the passage of radiation to the Earth; depending on the thickness of the cloud layer the blockage can become total (García *et al*., 2017).

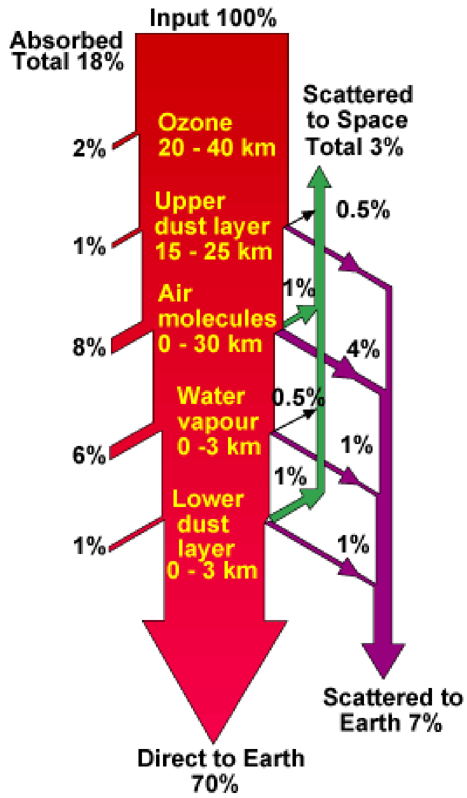

Figure 6 Factors influencing the attenuation of incident solar radiation
Source: (Based on IrSOLaV map)

In general terms, it is estimated that about 23% of the extraterrestrial solar radiation that strikes the atmosphere will be attenuated by the above phenomena before reaching the Earth's surface. Solar radiation at a wavelength between 0.29μm and 2.5 μm is the one that suffers scattering and absorption, since almost all radiation outside this interval is scattered and absorbed immediately.

Wavelengths longer than 2.5 μm have a high absorption by CO_2 as they pass through the Earth's atmosphere (Duffie *et al*. 2013).

Methodology

Zacatecas is located in the north-central region of the country with a temperate subtropical mountain climate. The average annual temperature is 17 °C, the average maximum temperature is around 30 °C and occurs in the month of May. The average minimum temperature is 3 °C and occurs in the month of January.

The state average rainfall is 210 mm per year, with rainfall occurring in the summer months from June to September.

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The dry and semi-dry climate of the state is a constraint for agriculture, which is practiced in irrigated and rainfed agriculture, the main crops being: corn, oats, wheat, beans, chili sorghum, cactus and peaches. Table 1 shows the main characteristics of the evaluation area.

Location	Center - north region
Weather	Temperate subtropical
Maximum Temperature	30 °C
Minimum Temperature	3 °C
Average precipitation	210 mm

Table 1 Measurement site characteristics
Source: INEGI 2018

The data were obtained at the Solarimetric Station Zacatecas_04 (Figure 7) located in Building E6 of the Academic Unit of Chemical Sciences in the Academic Program of Chemical Engineering at the UAZ Siglo XXl Campus located at Carretera Zacatecas - Guadalajara km. 6, ejido "La Escondida", Zacatecas, Zac. With coordinates Latitude (N) 22.7725 N Longitude (W) - 102.6436 and an altitude of 2317 masl (meters above sea level). The station is part of the Mexican Solarimetric Network of the Mexican Solarimetric Service of the Institute of Geophysics of the Autonomous University of Mexico, which is an integral system of measurement, validation and publication, with permanent maintenance of specialized equipment for the measurement of solar radiation, which allows generating reliable information for the exploitation of solar energy for any type of user.

Figure 7 Solarimetric station Zacatecas_04
Source: Own

The data acquisition (taken every two seconds and averaged every minute) was performed with a Campbell Scientific CMP 22 Kipp and Zonen pyranometer (Figure 8), the data acquisition is done in a CR3000 datalogger of the same company, both are installed in the Zacatecas_04 Solarimetric Station.

Figure 8 Global radiation pyranometer on inclined plane
Source: Own

The specifications of the CMP 22 inclined plane pyranometer used are presented in Table 2.

Spectral range (total)	200 A 3600 nm
Sensitivity	7 a 14 μV/W/m^2
Response time	5 s
Offset zero A	< 3 W/m^2
Offset zero B	< 1 W/m^2
Directional error (up to 80° at 1000 W/m2)	< 5 W/m^2
Temperature dependence sensitivity: (-20°C a +50°C)	< 0.5%
Operating temperature range	-40° C a 80°C
Maximum solar irradiance	4000 W/m^2
ISO Classification 9060:2018	Espectralmente Plana Clase A

Table 2 Specifications of Pyranometer CMP 22 Kipp and Zonen
Source: (https://www.kippzonen.es /Product/212/CMP22-Piranometro#.XP_ nhshKjIU, 2019)

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The data that were collected for analysis comprise January 01, 2018 through the period of December 31, 2018. They were rearranged into average per hour, average per day, average per month, average per day-month, average per hour-month. Subsequently, the hour in which the sensor recorded the highest Irradiance for the inclined plane was identified, as well as the hour in which the sensor recorded values close to or equal to zero for the inclined plane, corresponding to sunrise and sunset. With the approximate time of both sunrise and sunset, the Irradiance data of interest from the sensor was set, with such data, graphs were obtained with the monthly averages of time and day of the year.

Results

With respect to the Inclined Plane Pyranometer, a comparison was made of the highest and lowest Irradiance, which could be visualized by means of a graph, for the months of March (highest Irradiance of the year, Figure 9) and November (lowest Irradiance of the year, Figure 10). It should be noted that the averages were made for the Global Horizontal and Inclined Plane Pyranometers in order to make a graphical and numerical comparison of the averaged results.

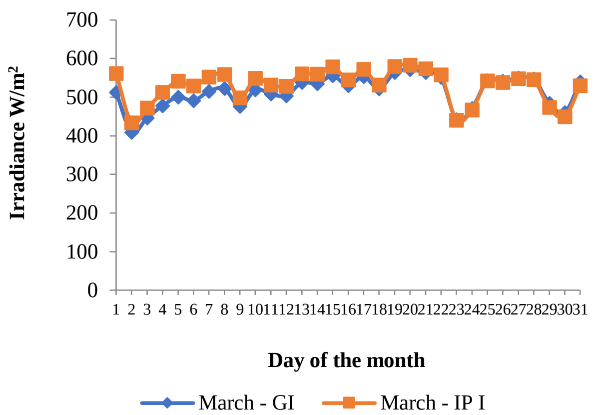

Figure 9 Average Irradiance for the month of March of the Tilt Plane Pyranometer vs Global Horizontal Pyranometer

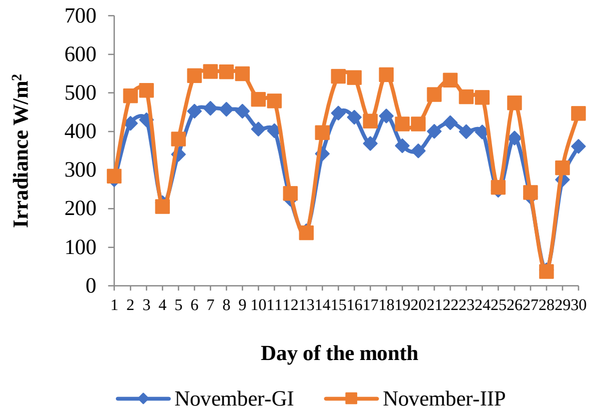

Figure 10 November Average Irradiance of the Tilt Plane Pyranometer vs Global Horizontal Pyranometer

Figure 11 shows the annual average hourly Irradiance evaluated in the Inclined Plane Pyranometer.

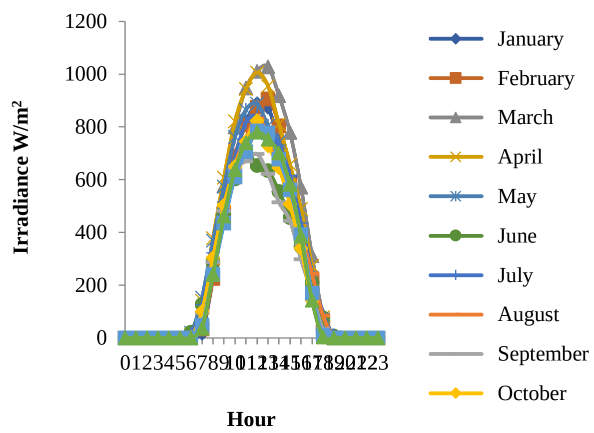

Figure 11 Average Annual Irradiance measured on the Inclined Plane

Equation 1 is the mathematical correlation found between the Global Horizontal and Tilt Plane pyranometer measurements.

$$I_{PI} = 1.022 - 1.157\, G_H \qquad (1)$$

Where:

G_H = *Irradiancia Global medida en el Plano Horizontal*

I_{PI} = *Irradiancia calculada para el Plano inclinado*

The error found is 11% using the model. Figure 12 shows the graphical comparison of the model obtained and the real data.

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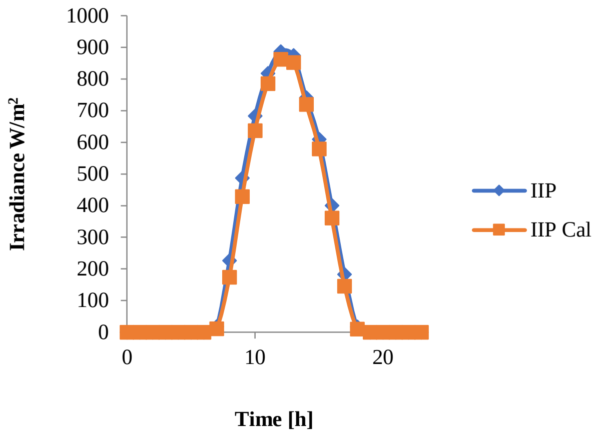

Figure 12 Comparison of measured Irradiance and calculated Irradiance for the month of January

Conclusions

Based on the data obtained on March 1, 2018, was the day with the highest irradiance at 12:00 p.m., with a value of 1063.569 W/m^2. Similarly, on November 28, 2018, the lowest value was recorded and equal to 30.841 W/m^2.

The mathematical model obtained to correlate the measurements between the Inclined and Horizontal Plane pyranometers presents an error of 11%, which can be considered acceptable.

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