ORIGINAL ARTICLE

Modeling of solar radiation for the photovoltaic pumping system in sprinkler irrigation

Modelación de la radiación solar para el sistema de bombeo fotovoltaico en el riego por aspersión

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Yaily Beltran Perez[I]*, Oscar Brown Manrique[II], Nestor Mendez Jurjo[II], Isaí Álvarez Sevilla[III]

[I]Cooperativa de Producción Agropecuaria 8 de marzo, Ciego de Ávila, Cuba.
[II]Universidad de Ciego de Ávila Máximo Gómez Báez (UNICA), Ciego de Ávila, Cuba.
[III]Instituto de Fomento Municipal, Guatemala.

ABSTRACT: Mathematical models are fundamental for the simulation of solar radiation; allowing the effective design, optimization of the performance of photovoltaic systems and guaranteeing a stable supply of electrical energy. The present study was developed at the Delia Cooperative Basic Production Unit with the objective of estimating solar radiation for the photovoltaic pumping system for sprinkler irrigation in bean cultivation. The methodology used consisted of the application of the Hottel model to determine the components of solar radiation on a horizontal surface and the Solener method based on the inclination of the surface of the photovoltaic panel. The results showed that the global solar radiation that occurs on a horizontal plane for the municipalities of Venezuela, Primero de Enero, Morón and Sancti Spiritus in the different months of the year varies between 3952.07 and 10626.30 W m^{-2} day^{-1}. The global solar radiation that falls on the surface of the photovoltaic panel placed with an inclination of 21º allows increasing the value of this variable between 12 and 30%, improving the number of peak sun hours daily for the operation of the photovoltaic generator.

Keywords: components of solar radiation, solar energy, photovoltaic panel.

RESUMEN: Los modelos matemáticos son fundamentales para la simulación de radiación solar, ya que el diseño eficaz, la optimización del rendimiento de los sistemas fotovoltaicos y garantizan un suministro estable de energía eléctrica. El presente estudio se desarrolló en la Unidad Básica de Producción Cooperativa Delia con el objetivo de estimar la radiación solar para el sistema de bombeo fotovoltaico del riego por aspersión en el cultivo del frijol. La metodología utilizada consistió en la aplicación del modelo de Hottel para determinar las componentes de la radiación solar sobre superficie horizontal y el método de Solener en función de la inclinación de la superficie del panel fotovoltaico. Los resultados demostraron que la radiación solar global que se produce sobre un plano horizontal para los municipios de Venezuela, Primero de Enero, Morón y Sancti Spiritus en los diferentes meses del año varía entre 3952,07 y 10626,30 W m^{-2} $día^{-1}$. La radiación solar global que incide sobre la superficie del panel fotovoltaico colocado con una inclinación de 21º permite incrementar el valor de esta variable entre 12 y 30% mejorando la cantidad de horas de sol pico diariamente para el funcionamiento del generador fotovoltaico.

Palabras clave: componentes de la radiación solar, energía solar, panel fotovoltaico.

INTRODUCTION

Knowledge of global solar radiation is essential for many applications, such as the use of solar energy as an alternative source, crop growth simulation models, architecture, system design, evapotranspiration estimation, among others; however, the availability of global solar radiation data is scarce, making the use of numerical techniques an essential alternative. With such indirect techniques, other meteorological data are mathematically explored in order to estimate the amount of global solar radiation reaching the earth and global radiation (Ayllón, 2012).

*Author for correspondence: Yaily Beltran-Perez, e-mail: yailybeltran@gmail.com

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The determination of solar radiation is a strategic objective for the development of society De la Casa et al. (2023); however, the measurement of this variable is only carried out in a limited number of meteorological stations Goodin et al. (1999) and as a consequence it is the least evaluated element of the climate and constitutes information of limited availability.

Food production requires, among many aspects, the supply of basic resources such as water and electrical energy, which is achieved through irrigation systems that allow a more rational use of water for the optimal development of crops; but at the cost of an increase in the demand for electrical energy; however, rural areas do not always have a nearby electrical energy network, so the use of photovoltaic solar energy constitutes a sustainable solution that improves the performance of agricultural activity (García et al., 2013; Ferreira et al., 2022).

On the other hand, the difficulty in obtaining daily global radiation data due to the high cost and maintenance of measurement equipment has led to the development of models to estimate this meteorological variable (Miller et al., 2008). Based on the above, the objective of this work is to model solar radiation for the photovoltaic pumping system in sprinkler irrigation.

MATERIALS AND METHODS

The experiment was carried out at the Delia Basic Cooperative Production Unit (UBPC), located in the Primero de Enero municipality in the province of Ciego de Ávila, at 21º 45' North latitude and 78º 14' West longitude. The soil is of the Typical Red Ferralitic type and correlates with the Ferralsols order according to the global reference base for the soil resource WRB (Palma et al., 2017). Its main hydrophysical characteristics are presented in Table 1 with a wilting point of 21.22% based on dry soil (bss) and infiltration rate of 2.20 mm day^{-1}.

Solar radiation on a horizontal plane, at ground level, was simulated using the Hottel model Álvarez et al. (2021) which calculates the radiation transmitted through the clear atmosphere, depending on the zenith angle, the altitude for a standard atmosphere and type of climate. The direct radiation as a function of the zenith angle is given by the expression:

$$R_{DIR(\theta_Z)} = a_o + a_1 \cdot e^{\left(\frac{-k}{\cos\theta_Z}\right)} \quad (1)$$

$$a_o = r_0\left[0.4237 - 0.00821(6.0 - Z)^2\right] \quad (2)$$

$$a_1 = r_1\left[0.5055 + 0.00595(6.5 - Z)^2\right] \quad (3)$$

$$a_k = r_k\left[0.2711 + 0.01858(2.5 - Z)^2\right] \quad (4)$$

Where $R_{DIF(\theta z)}$ is the diffuse radiation with respect to the zenith angle (W m^2 day^{-1}), a_0, a_1 and k are constants, Z the altitude of the locality above sea level (km); r_0, r_1 and r_k the correction factors that acquire values of 0.95, 0.98 and 1.02 respectively for the tropical climate according to 02 respectivamente para el clima tropical según Álvarez et al. (2014); Mossande et al. (2015).

The solar declination, δ (º), which indicates the angular position of the Sun at solar noon, with respect to the plane of the equator, takes into account the day of the year, d_a, and the cosine of the zenith angle, θ_z, which shows the position of the Sun with respect to the vertical. This parameter was calculated as follows:

$$\delta = 23.45 sen\left[\frac{2\pi(284 + d_a)}{365}\right] \quad (5)$$

$$\cos\theta_z = \sin\phi \cdot \sin\delta + \cos\phi \cdot \cos\delta \cdot \cos\omega_s \quad (6)$$

$$\omega_s = \cos^{-1}(-\tan \emptyset) \cdot \tan\delta \quad (7)$$

Where ϕ is the geographical latitude (º), which indicates the angular position of the place where the photovoltaic panel is located with respect to the Earth's equator. It is positive in the northern hemisphere and negative in the southern; ω_s the hour angle at dawn or dusk (radians).

The diffuse radiation on the horizontal surface, as a function of the zenith angle, was calculated by the equation of Liu & Jordan (1960) and the direct, diffuse and global radiation on the horizontal plane were determined according to the following equations:

$$R_{DIF(\theta_z)} = 0.2710 - 0.2939 R_{DIR(\theta_z)} \quad (8)$$

$$R_{DIR(0)} = R_{DIR(\theta_z)} R_{E(o)} \cos\theta_z \quad (9)$$

$$R_{DIF(0)} = R_{DIF(\theta_z)} R_{E(o)} \cos\theta_z \quad (10)$$

TABLE 1. Hydrophysical properties of the soil

Depth (cm)	Field capacity (% bss)	Density apparent (g cm^{-3})	Sand %	Silt %	Clay %
0 - 10	35,10	1,03	19,50	20,01	60,49
11 - 20	34,46	1,03	18,42	17,26	64,32
21 - 30	35,48	1,03	21,80	15,92	62,28
31 - 40	35,41	1,07	17,40	18,.00	64,.60

$$R_{G(0)} = R_{DIR(0)} + R_{DIF(0)} \quad (11)$$

Where $R_{DIR(0)}$ is the direct radiation (W m^2 day^{-1}), $R_{DIF(0)}$ the diffuse radiation (W m^2 day^{-1}), $R_{E(0)}$ the daily monthly extraterrestrial radiation on a flat surface (W m^2 day^{-1}), $R_{G(0)}$ the global radiation (W m^2 day^{-1}).

The determination of the components of solar radiation based on the inclination of the surface of the photovoltaic panel was carried out based on prior knowledge of global radiation, extraterrestrial radiation, direct radiation, diffuse radiation on a flat surface and the reflectivity coefficient or albedo (ρ) with a value of 0.20 (López *et al.*, 2023). The panel incline, clarity index and diffuse fraction were obtained from the following equations:

$$I_C = \frac{R_{G(0)}}{R_{E(0)}} \quad (12)$$

$$F_{DIF} = \frac{R_{DIF(0)}}{R_{G(0)}} = 1 - 1.13 I_C \quad (13)$$

Where I_C the Clarity Index (adim.), $R_{G(0)}$ the global radiation (W m^2 day^{-1}), F_{DIF} the diffuse fraction (adim.).

The direct, diffuse, reflected and global radiation on the inclined surface of the photovoltaic panel were obtained as:

$$R_{DIR(\beta)} = R_{G(0)}(1 - F_{DIF}) R_B \quad (14)$$

$$R_{DIF(\beta)} = \frac{1 + \cos\beta}{2} R_{G(0)} I_C \quad (15)$$

$$R_{REF(\beta)} = \frac{1 - \cos\beta}{2} \rho R_{G(0)} \quad (16)$$

$$R_{G(\beta)} = R_{DIR(\beta)} + R_{DIF(\beta)} + R_{REF(\beta)} \quad (17)$$

Where $R_{DIR(\beta)}$ the direct radiation (W m^2 day^{-1}); $R_{DIF(\beta)}$ the diffuse radiation (W m^2 day^{-1}); $R_{REF(\beta)}$ the reflected radiation (W m^2 day^{-1}); $R_{G(\beta)}$ the global radiation (W m^2 day^{-1}).

RESULTS AND DISCUSSION

Figure 1 shows the behavior of global solar radiation referred to a horizontal surface for the Primero de Enero municipality. These values were obtained from mathematical simulation using the Hottel method. The behavior of global radiation can be observed in the different months of the year, finding values between 3952.07 and 10626.30 W m^{-2} day^{-1}, which is the range of photovoltaic solar energy available in these locations. for the generation of electrical energy necessary for the operation of irrigation systems powered by this type of renewable energy.

The average value of this variable ranges between 6.5 and 8.3 kW m^{-2} days^{-1} in the province of Ciego de Ávila; while the map of solar radiation in Cuba, prepared by the Cuban Institute of Meteorology, offers values between 6.4 to 6.6 kW m^{-2} days^{-1}. The differences may be attributable to the fact that these values are accurate estimates in the country; but they do not respond to systematic measurements carried out in these localities; since they lack the instruments required for this type of observation.

Figure 2 shows the behavior of global solar radiation for a panel inclination of 21°, which is recommended for photovoltaic systems in Cuba. It is observed that the values vary between 4657.26 and 18656.07 W m^{-2} day^{-1} throughout the year; the highest solar energy corresponds to the months of April, May, June, July, August and September, which presented values greater than 11400 W m^{-2} day^{-1}. The dynamics of solar radiation indicates a notable decrease in this variable in the months of November, December and January; with values of 5147.93; 4124.19 and 4657.26 W m^{-2} day^{-1} respectively.

The use of a certain inclination of the panel is an aspect of great importance in the design of photovoltaic systems because in addition to allowing greater coverage of incident solar radiation, it also offers the advantage of guaranteeing water drainage and reducing the accumulation of dust on the panel surface. In this sense, studies carried out in Cuba by

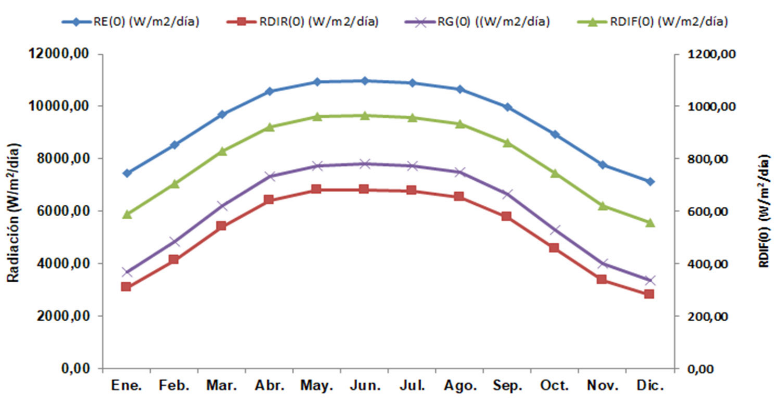

FIGURE 1. Solar radiation on a horizontal surface.

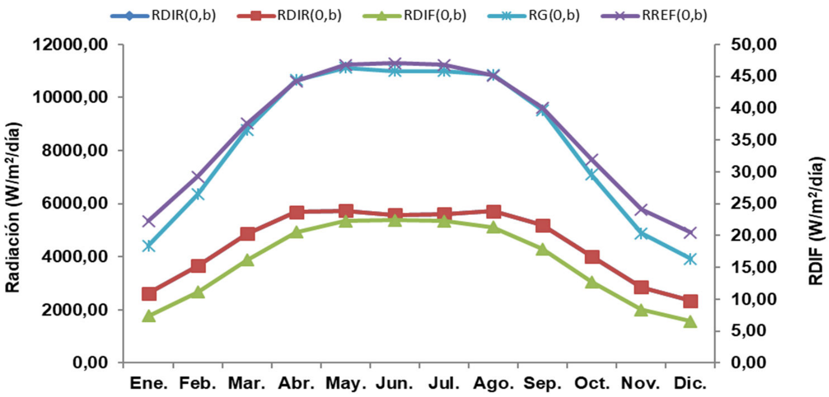

FIGURE 2. Solar radiation on the photovoltaic panel with an inclination of 21º .

Díaz *et al.* (2018) where they analyzed the influence of the angle of inclination in the solar modules on the generation of a photovoltaic plant, made it possible to verify that the optimal angle of inclination is equal to the latitude of the place where the photovoltaic parks are going to be installed.

The estimation of global solar radiation through mathematical modeling is of great importance for the conditions of the municipalities of the province of Ciego de Ávila, due to the lack of instruments for measuring this climatic variable. The application of tools of this type favors many countries that do not have meteorological stations for measuring solar radiation data, which is required to determine the potential and performance of photovoltaic systems (Andrade & Blacutt, 2010).

Grajales (2018) carried out the validation of different models for estimating incident solar radiation on a horizontal surface in the municipality of Dosquebradas, department of Risaralda in Colombia. In the process, a simulation of solar radiation on optimally inclined surfaces was also carried out; obtaining satisfactory results in all cases.

In this sense, Mossande *et al.* (2015) applied the Hottel and Solener Model to estimate solar radiation in conditions of a horizontal plane and the inclination of the photovoltaic panel according to the latitude of the place. The results obtained were satisfactory and were used in the design of a solar photovoltaic drip irrigation system for tomato production in the Cavaco Valley , Republic of Angola, in an experimental area of 0,23 ha. The evaluations carried out regarding the management and operation of the system demonstrated the validity of the methodology used for the arid conditions prevailing in this locality.

CONCLUSIONS

- The global solar radiation produced on a horizontal plane estimated by the Hottel model for the Primero de Enero municipality varies between 3952.07 and 10626.30 W m^{-2} day^{-1}.
- The global solar radiation that falls on the surface of the photovoltaic panel placed with an inclination of 21º estimated by the Solener model allows the value of this variable to be increased between 12 and 30%.
- In the municipalities evaluated it is possible to have between 4.0 and 6.4 hours of peak sunshine daily in the most critical months of the year. These are data that must be taken into account for the design of the photovoltaic generator.

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Yaily Beltran-Perez. MSc., Especialista Principal, Cooperativa de Producción Agropecuaria 8 de Marzo, Ciego de Ávila, Cuba.
Oscar Brown-Manrique. Dr.C., Prof. Titular, Universidad de Ciego de Ávila Máximo Gómez Báez (UNICA), Centro de Estudios Hidrotécnicos (CEH), Ciego de Ávila, Cuba. e-mail: obrown@unica.cu
Nestor Mendez-Jurjo. Dr.C., Prof. Titular, Universidad de Ciego de Ávila Máximo Gómez Báez (UNICA), Departamento de Ingeniería Hidráulica, Ciego de Ávila, Cuba. e-mail: nestorm@unica.cu
Isaí Álvarez-Sevilla. Dr.C., Supervisor de Obras, Instituto de Fomento Municipal, Guatemala. e-mail: aisaithomas2002@gmail.com