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Simulation of the Effect of the Angle of Incidence on the Solar Panel for Three Solar Photovoltaic (Pv) Systems in the Bogotá Savanna– Subparamo

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The planet's pollution from greenhouse gases resulting from fossil energy sources' inefficient use, has made the scientific community reflect and has led it to search for new alternative and renewable energy sources to supply increasing energy needs. One of the sources that have had significant growth worldwide in the last decade is photovoltaic solar energy. However, one of the drawbacks with the use of photovoltaic technology is conversion efficiency. For this, alternatives are sought, such as the study of new materials with structures that facilitate the quantum photodetection of a given compound; minimize losses due to transient and harmonic in the regulation devices and inverters, and losses in the storage and transport of the energy generated. One proposal to increase the collection efficiency is solar tracking systems, making the panels remain approximately perpendicular to the direct light beam (direct radiation), from dawn to sunset. In this research work, three photovoltaic solar energy capture systems are compared using a simulation. The first case corresponds a fixed system in a horizontal position; the second case is a system fixed with an inclination of 10 degrees south latitude, and the third, a two-axis tracker. The information collected is taken in the municipality of Sibaté, the coordinates 4 ° 30 ' 09.5 " N, 74 ° 15 ' 20.2 " W in the Savanna of Bogotá. The purpose of this study is to use clean electrical energy to obtain bio-hydrogen using electrolysis. In the simulation, two periods, cloudy and clear, are determined based on a threshold taken experimentally in the panels and thus comparing the three systems. The results show that in clear periods the solar tracker has an energy conversion gain of 5 %. On the other hand, in cloudy periods, the three systems' panels showed similarity in the energy measurements captured.

1. Introduction

The pollution of the planet from gases that cause the greenhouse effect, a product of the inefficient use of fossil energy sources, has made the scientific community reflect and has led it in the search for new alternative and renewable energy sources to meet growing energy needs (Cediel et al. 2003). One of the sources that have had significant development and growth worldwide in the last decade is photovoltaic solar energy (PV) (REN21, 2020).

Several photovoltaic solar systems have been developed, which vary by their configurations depending on the use. However, there is a coincidence for all it is necessary to work in search of improving the conversion efficiency (Zoe, 2018; Shockley, 1961). Direct radiation on a sunny day can be up to 90 % of total solar energy, and the remaining 10 % corresponds to diffuse radiation (Gueymard, 2002). This research addresses the problem of radiation incidence received by solar panels. Since if the panels remain oriented so that direct solar irradiation falls on them at an angle of 90 °, it is possible to increase the intensity of energy absorbed by the solar panel, despite the relative movement of the earth to the sun for a day.

Numerous investigations are reported that are directed towards improving the conversion efficiency of photovoltaic systems. A study carried out by the General Motors R&D Center, and the Chemical & Environmental Sciences Laboratory in Detroit (USA) shows that the highest energy conversion from photovoltaic systems with two-axis tracking occurs on clear days. If compared to modules installed with a fixed inclination (without movement to track the light beam), where the energy transformation is calculated to have increased between 30 and 50 %, this is achieved because the energy received by the panels with tracker corresponds largely to direct radiation (Nelson & Kelly, 2009).

General Motors (GM) published another work carried out in the test field by the same group of researchers, in which the performance of four fixed systems with the same characteristics located in four positions, inclined 0 °, 27 °, 42 °, and 57 ° south latitude, in order to study the incidence of the inclination on the captured energy and it was compared with a two-axis tracking system. This test was carried out for eight months in the city of Milford (MI, USA). They found that, on sunny days, the energy captured by the monitoring system was twice that of the one located horizontally (0 °). The analysis shows that solar tracker reduces solar energy harvesting compared to the horizontally located system on cloudy days. A gain of 37 % was obtained in the horizontal position system, and it is estimated that a gain of 50 % would be obtained (Nelson & Kelly, 2011).

On the other hand, the Observatory Road, Bouzareah and the Universities Amar Teldji University, University A. Mira and National Polytechnic School, Algiers, Algeria, published a review of the main methods used for the capture of photovoltaic energy under different environmental conditions. They reach conclusions very similar to those already mentioned, that is, for clear or sunny periods, the advantage is given for two-axis trackers, and cloudy periods, the highest gains were obtained from systems arranged horizontally (Koussa et al. 2011).

Recently, at Deemed University in the city of Bengaluru (India), an investigation was carried out where the performance of a solar tracker PV energy harvesting system is compared with another previously used fixed system, an increase of between 15 and 20 % depending on weather conditions (Rameez et al. 2020).

In this research work, three photovoltaic solar energy capture systems are compared using a simulation. The first case corresponds to a fixed system in a horizontal position; the second case is a fixed system with an inclination of 10 degrees south latitude, and the third, a two-axis tracker. The research will be carried out in the municipality of Sibaté located at coordinates 4 ° 30 ' 09.5 " N, 74 ° 15 ' 20.2 " W, on the Bogotá Savanna. Sibaté is located at an altitude of 2630 meters above sea level (masl) and an average temperature of 14 ° C, spread over a sub-paramo thermal floor (Codazzi, 2002), with an unstable climate, as well as cold, cloudy, and rainy, although there are hours of intense sun (Hofstede, 2003). These conditions generate uncertainty regarding the amount of radiation that a PV system can capture, despite being located in the tropics, this reason to simulate the three systems in order to evaluate which one can be used to obtain biohydrogen through the electrolysis process.

2. Material and methods

2.1 Incident radiation

The incident irradiation on the earth's surface is affected by three factors: solar constant, distance from the sun, and attenuation due to atmospheric transparency..

Solar constant (I_0) is the amount of energy from the sun perpendicularly incident on a surface of unit area per unit time placed outside the earth's atmospheres or terrestrial sphere at an average distance of 150 x 106 Km of the sun. The current value is estimated at 1370 W / m^2 and ranges approximately 1.2 W / m^2 (NASA SCIENCE, 2003).

Distance to the sun: The earth's translational movement in the earth's orbit changes the earth-sun distance during the year, causing a variation in the solar radiation outside the earth's atmosphere. Analytically, the incident extraterrestrial radiation can be found through the expression of Eq(1):

$$I_n = I_0 (R_0/R) \tag{1}$$

Where I_0 is the solar constant, R_0 is the mean radius of the constant Earth orbit and R is the radius that varies with the translational motion

Attenuation by atmospheric transparency: caused by gases such as atomic oxygen, nitrogen in the upper layers of the atmosphere, selective absorption by water vapor, and other gases in lower layers. (UPME, 2005).

2.2 Direct radiation

It is the flow of radiation that reaches the earth's surface without having been affected in its direction. The solar panel position to the sun relative defined by the elevation angle (h) and angle azimuthal (a). The relationship that joins the elevation angle and azimuthal with the time of day and direct solar radiation (Ib) is given by Eq(2):

Ib = Ibh*Cos(b) (2)

Where Ibh is the horizontal direct irradiation
In Eq(3), it sees the value of cosine:

Cos(b) = *n.k* (3)

n is the unit normal to the surface of the solar panel. The value of the vector is shown in Eq(4)

n[sin(γ)sin(i)cos(γ), sin(i)cos(γ), cos(i)] (4)

γ angle to south
i angle of inclination to the horizon
k is the unit vector that indicates the direct sunlight beam's direction. The value of the vector is shown in Eq(5).

K[cos(h)sin(a), cos(h*sin(a), sin(h)] (5)

Now, these expressions are substituted into equation 2 for being as shown in Eq(6)

Ib = Ibh*[sin(i)cos(h) cos(a - γ), cos(i)sin(h)] (6)

2.3 Diffuse radiation

The dispersion of solar irradiation can be seen in Figure 1. We start from the extraterrestrial solar irradiation (Ic), which is a constant value. This value reaches the atmosphere with a small variation, a product of the earth's elliptical path, known as extraterrestrial radiation (I_{ext}). Upon reaching the earth's atmosphere, it fragments, 30 % is reflected, 23 % is absorbed (ultraviolet component due to ozone and an infrared component due to water vapor), dispersed by molecules of gases, water, and particles existing in the air, a part is reflected in the clouds. Finally, 47 % reaches the earth in the form of direct radiation (I_{bh}). Of the reflected and scattered components, a part reaches the planet in diffuse radiation (I_{dh}). (Iqbal, 1983), (UPME, 2005).

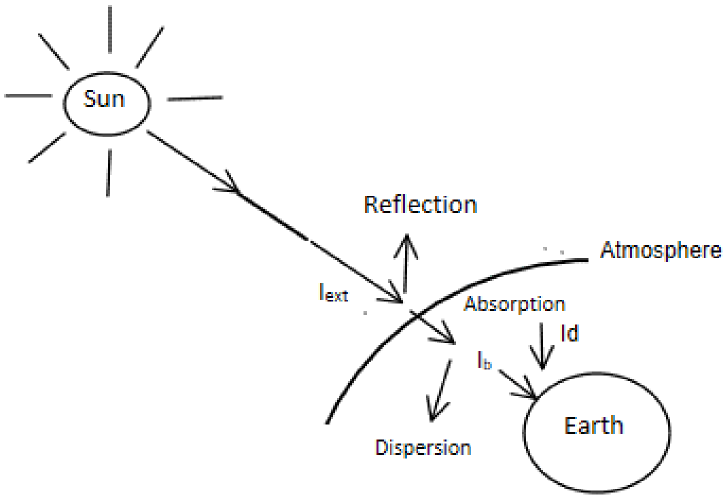

Figure 1: Scheme of the effect of the atmosphere on solar irradiation

Eq(7). is shown that the global horizontal irradiation (Gh) is the sum of the direct irradiation (Ibh) plus the diffuse irradiation (Idh).

Gh = Ibh + Idh (7)

When the panels are in a horizontal position, when inclined with an angle (i) compared to the horizontal, a part of the diffuse radiation comes from the ground. In this case, the fraction of the diffuse radiation resulting from the sky is expressed in Eq(8):

$$Idatm = \frac{1 + \cos(i)}{2} * Idh \quad (8)$$

The diffuse irradiation resulting from the ground received, Eq(9), by the solar panels is:

$$Idsol = \frac{1+\cos(i)}{2} * Gh * a \quad (9)$$

Where: a is the albedo, which corresponds to the percentage of radiation that any surface reflects, and its mean value is 0.3.

Indirect solar radiation is the sum of two diffuse fluxes and can be expressed, as shown in Eq(10):

$$Idif = \frac{1+\cos(i)}{2} * Gh * a + \frac{1+\cos(i)}{2} * Idh \quad (10)$$

With Idh expressed in Eq(11):

Idh = Gh – Ibh*sin(h) (11)

2.4 Total radiation

The total radiation (Gt) received by solar panels corresponds to the superposition of direct radiation and diffuse radiation. The sum of direct and diffuse light leads to the following relationship expressed in Eq(12):

$$Gt = Ib + Idif \quad (12)$$

2.5 Mathematical model of Photovoltaic cells

The mathematical model of a solar cell has been studied for more than three decades; its equivalent circuit consists of a current source generated by solar irradiation, in parallel with a diode, and a resistance, R_{SH} and a resistance in series, Rs that represents the internal resistance of the material to the flow of the generated current. The mathematical model is obtained from the electrical representation and is a function of solar irradiation and cell temperature. The characteristic equation (Eq(13)) corresponding to the model is:

$$I = I_{PH} - Is\left[\exp\left(\frac{q}{kT_cA}(V+IR)\right) - 1\right] - V + \frac{IR_s}{R_s} \quad (13)$$

Where I_{PH} is a photocurrent, I_s is the inverse saturation current of the cell, q represents the charge of the electron (1.6 x 10^{-19} C), k is the Boltzmann constant (1.38 x 10^{-23} J / K), T_C is the cell operating temperature in Kelvin, (K), A is an ideality factor, R_{SH} is the shunt resistance or leakage current, and R_S is the internal series resistance of the circuit. The photovoltaic current or photocurrent depends mainly on the intensity of insolation and operating temperature, as seen in Eq(14):

$$I_{PH} = \left[I_{SC} + K_l(T_C - T_{Ref})\right]\lambda \quad (14)$$

Where I_{sc} is the short-circuit current of the cell under standard conditions, that is, at 25 ° C and 1 KW / m^2 of solar irradiance. K_l is the temperature coefficient of the cell short-circuits current in A / ° C, Tc is the cell's operating temperature. T_{Ref} is the cell's reference temperature, and λ is the ratio of solar irradiation in the field to the standard. The saturation current of the cell varies with temperature, and is described as expresses in Eq(15):

$$I_s = I_{RS}\left(\frac{T_C}{T_{Ref}}\right)^3 exp\left[\frac{qE_G}{kA}\left(\frac{1}{T_{Ref}} - \frac{1}{T_C}\right)\right] \quad (15)$$

Being I_{RS} the inverse saturation current of the cell for the reference temperature and solar radiation. E_G is the bang-gap (forbidden energy gap) of semiconductor energy or energy difference between the upper part of the valence band and the lower part of the cell's conduction band. The ideal factor A depends on the photovoltaic technology. For the simulation of the Math model, the Matlab tool was used.

3. Results and discussions

Various simulations are obtained from the mathematical models exposed, in which geographic location and date must be determined to have greater precision in the simulation. The information collected is taken in the municipality of Sibaté, at coordinates 4 ° 30 ' 09.5 " N, 74 ° 15 ' 20.2 "W, altitude 2630m above sea level, in Colombia.

Initially, a comparison is made for sunny days between the system with a solar tracker and two fixed positions inclined 20 ° and 30 ° with a south direction. The comparison evaluates the incidence of the inclination angle. It is observed in Figure 2 that the solar tracker has a maximum intensity of 930 W / m ^{2}. In the fixed panel inclined 30 °, the transformed power decreases drastically to a value of 790 W / m ^{2}. In contrast, for the 20 ° inclination, it is 870 W / m ^{2}. The difference between the solar tracking system and fixed panel at 30 ° from the horizontal is approximately 15 % in this simulation.

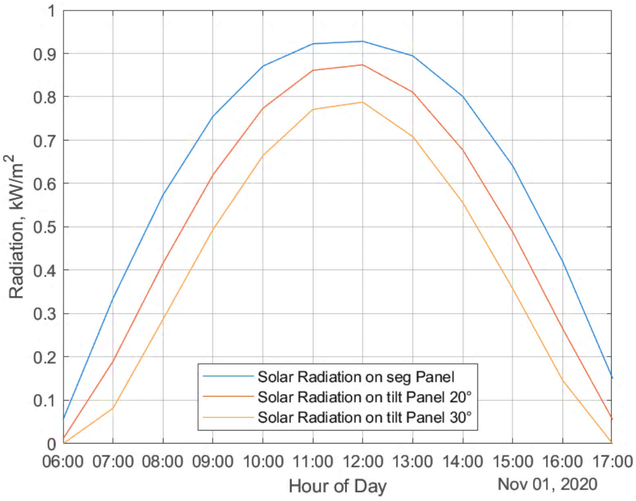

Figure 2: Comparison of the solar tracker with two fixed positions

Next, simulate a solar tracker, a horizontal solar panel, and a 10 ° inclined solar panel on a clear day, obtaining higher gains in the solar tracker, between 5 % and 7 % compared to fixed panels. The solar panel placed horizontally, and the solar panel tilted 10 ° have very similar values as seen in Figure 3a. The 10 ° tilt because the position is used optimally to prevent water accumulation in times of rain.

In Figure 3b simulation for panels is presented, solar tracker, fixed horizontal and fixed inclined 10°, in this graphic no differences were observed between them it can be caused by that day dark as radiation received by the panels it is the diffuse one, and due to the position in which the three systems are found they accumulate equal intensity.

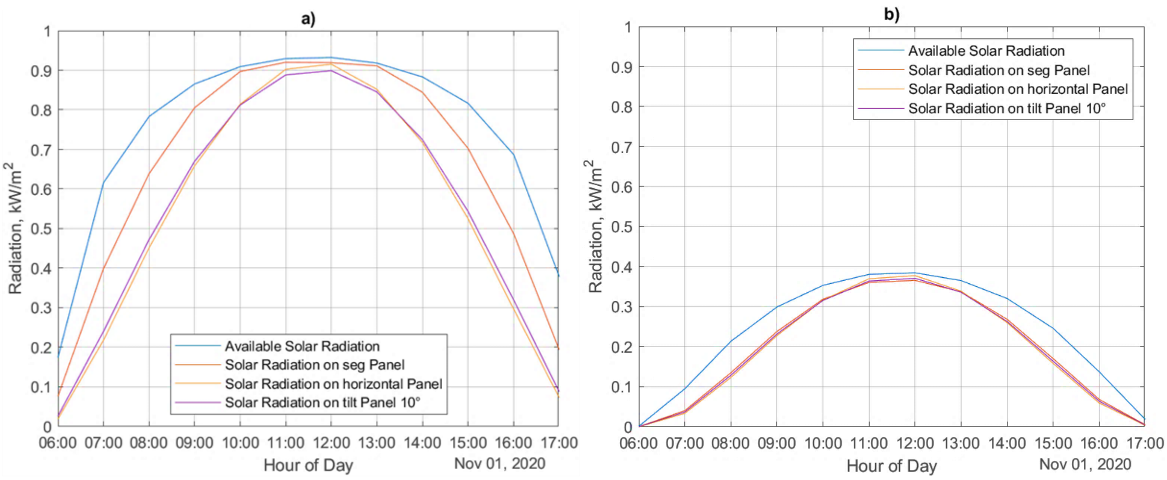

Figure 3: Comparison of the solar tracker, horizontal panel, and inclined 10 °: a) clear day b) dark day

The previous contrasts with reports of gain in two-axis tracking systems on sunny days, reaching up to 50 % like that obtained in Detroit (Nelson & Kelly, 2011). That is a city located at latitude 42 º to the North or with those reported in Jordan and Iran, in the order of 30 to 35%, whose location to the equator is approximately 32º north latitude (Abu-Khader et at. 2008) (MohsenMirzaei & ZamaniMohiabadi, 2018).

There seems to be a direct relationship between latitude and gain in tracking systems, as reported in Detroit at latitude 42 ° North, the gain is approximately 50 %, while in Jordan and Iran, in the order of 30 to 35 %, whose location to the equator is approximately 32 º north latitude. It is essential to highlight that the Bogotá savanna is in a sub-paramo climate; this condition causes prolonged periods of cloudiness, causing diffuse radiation to predominate throughout the day (Codazzi, 2002), making the ideal system either a fixed system located horizontally or with an inclination less than 10 ° south.

4. Conclusions

The theoretical results of the simulation of the three photovoltaic solar energy capture systems, solar tracker, fixed inclined 10 ° and fixed horizontal, show that for sunny days the solar tracker converts between 5% and 7% more energy than any other system evaluated. The comparison on dark days the energy captured by the three systems is similar between them, it does not present significant differences, this contrasts with reports of gain in two-axis tracking systems on sunny days, which can reach up to 50% as the one obtained. in Detroit (Abu-Khader, 2008). city that is located at latitude 42º north, or with those reported in Jordan and Iran, in the order of 30 to 35%, whose location with respect to the equator is approximately 32º north latitude (Nelson & Kelly, 2011).

It is important to bear in mind that the Savanna of Bogotá is located in a sub-paramo climate; this condition causes prolonged periods of cloudiness, causing diffuse radiation to predominate throughout the day. It is proposed to design an energy capture system that, on sunny days, tracks the solar disk to capture direct radiation and, on cloudy days, moves to a horizontal position to capture diffuse radiation caused by clouds.

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