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Mathematical Modelling of Electric Energy Potential of Piedra Bolivar Campus of Cartagena University, Obtained from Solar Radiation

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Abstract : Solar radiation incident on the Cartagena city was studied in this research, as it can be harnessed to generate electricity from solar panels, contributing to reduce electricity demand.It was developed a mathematical model to determine the electric energy potential obtained from solar radiation incident on the Cartagena city. It was used the Angstrom -Prescott equation to predict radiation daily on the Piedra Bolivar Campus of university of Cartagena during a year.
Keywords: Solar Radiation, Solar Panels, Electric Potential, Solar Mathematical Modelling.

1. Introduction

New energy sources are necessary to reduce the ambient (environmental) pollution generated by fossil fuel[1]. The renewable energy sources, such as solar, wind and hydrogen, are alternatives for being clean. The energy solar is presented as an alternative to generate energy from solar radiation[2-3]. Other researchers have generated hydrogen from water electrolysis and Photoelectrochemical water splitting[4-8] and, while energy generated from wind were studied by[9-11]. Hydrogen is a fuel of high energy density by weight and it has different applications including fuel cells using different kinds of polymeric membranes to generate energy efficiently without pollutant release[12-20].

The concern for environmental damage has created a series of summits and environmental conferences, which seek to take action and make proposals to counter this situation. Colombia has participated in the recent summits such as Rio +20 and Rio +10 Summit; despite being a developing country, it contributed 0.2% of total greenhouse gases emitted into the atmosphere[21,22], which is a very alarming figure for the country. For this reason, Colombia and other countries like Japan, China, Taiwan, United States and European Union, mainly Germany[23], are trying to implement the use of other energy sources that contribute to the reduction emissions of these gases.

The city of Cartagena requires electric power of thermal power plants, as Termocartagena, when the consumed energy is high, which constantly emits CO_2 into the atmosphere by burning fossil fuels.Cartagena is near the line of Ecuador, strategic location to conduct studies on solar energy; these studies have not yet had significance because of the high costs of installation and solar panels. Meanwhile, in Germany, although environmental conditions are not the best to implement the use of photovoltaics. This country becomes the first producer worldwide solar energy, managing to have more than a third of all global PV installed and accumulated

In this work will be studied the solar irradiance on the Cartagena city and it permits to determine the solar energy potential for installation of solar panel in the Campus Piedra Bolivar of Cartagena university. Furthermore, mathematical modelling was applied to determine the solar potential and efficiency of solar panel.

2. Mathematical modelling for determining the electrical potential of solar panels

Electrical energy generated using solar panel must to consider three principal variables, solar irradiance average on the inclined surface $(\overline{H}(\alpha,\beta))$, maximal potential of solar panel P_{pmp} and efficiency of solar panel (η_c) as expressed in Equation 1[24].

$$E_p = \frac{\overline{H}(\alpha,\beta)P_{pmp}\eta_c}{H_{CEM}} \quad (1)$$

Solar irradiance average on the inclined surface $\overline{H}(\alpha,\beta)$ was calculated using the equation 2, which depends of inclination constant $(\bar{R})$ and the month average of diary irradiance on the horizontal surface.

$$\overline{H}(\alpha,\beta) = \bar{R}\overline{H} \quad (2)$$

Inclination constant $(\bar{R}$) was calculated using equation 3 where $\overline{H}_d$ is the diffuse component; R_b is the month average of the diary radiation on horizontal surface; β is the surface inclination and r is the surface reflectance. Different angles (5°, 10°, 15°, 20°, 25°, 30°) were considered for the surface inclination, and 0.2 for reflectance of solar panel material.

$$\bar{R} = \left[\frac{(\overline{H}-\overline{H}_d)}{\overline{H}}\right]R_b + \left(\frac{\overline{H}_d}{\overline{H}}\right)\frac{(1+cos\beta)}{2} + \frac{r(1-cos\beta)}{2} \quad (3)$$

R_b and $\overline{H}_d$depend of the site latitude with respect to Ecuador (φ), in this case the Cartagena city is located Colombia north (10º 25' 30"). R_b was calculated using the equation 4

$$R_b = \frac{\cos(\varphi-\beta)\cos\delta\sin\omega_s + (\pi/180)\sin(\varphi-\beta)\sin\delta}{\cos\varphi\cos\delta\sin\omega_s + (\pi/180)\omega_s\sin\delta\sin\varphi} \quad (4)$$

where$(\boldsymbol{\omega_S})$the angle of sunrise and this is calculated with equation 5; declination of the sun$(\boldsymbol{\delta})$is your angular position atmidday with respect to the Ecuador plane, and it is calculated with equation 6.

$$\omega_S = \cos^{-1}(-\tan\delta\tan\varphi) \quad (5)$$

$$\delta = 23{,}45\ \sin\left[\frac{360}{365}(284+d_n)\right] \quad (6)$$

The diffuse component $(\boldsymbol{\overline{H}_d})$depends on the clarity factor, this was calculated by correlations of Collares-Pereira and Rabl (Equation 7):

$$\frac{\overline{H}_d}{H_0} = \begin{cases} 0{,}99 \quad (para\ K_{t2} \leq 0{,}17) \\ 1{,}1889 - 2{,}272K_{t2} + 9{,}473{K_{t2}}^2 \\ -21{,}865{K_{t2}}^3 + 14{,}648{K_{t2}}^4 \quad (para \quad 0{,}75 \leq K_{t2} \leq 0{,}8) \\ -0{,}54K_{t2} + 0{,}632 \quad (para \quad 0{,}75 \leq K_{t2} \leq 0{,}8) \\ 0{,}2 \quad (para\ K_{t2} \geq 0{,}8) \end{cases} \quad (7)$$

Monthlyclarity factor $(\boldsymbol{K_{t2}})$ is calculated (equation 8) with the monthly average of daily radiation $(\overline{H})$and solar radiation given atmosphere outside (H_0), which is calculated with equation 9.

$$K_{t2} = \frac{\overline{H}}{H_0} \quad (8)$$

$$H_0 = \frac{24H_{SC}}{\pi}\left(\frac{R_0}{R}\right)^2\left[\cos(\varphi)\cos(\delta)\sin(\omega_s) + \frac{\pi\omega_s}{180}\sin(\omega_s)\sin(\delta)\right] \quad (9)$$

whereH_{SC} is the solar constant; $\left(\frac{R_0}{R}\right)^2$ is the eccentricity correction factor, which was calculated with equation 10; d_n is the day number $1 \leq d_n \leq 365$; φ is the place latitude.

$$\left(\frac{R_0}{R}\right)^2 = 1{,}00011 + 0{,}034221COS\left(\frac{2\pi(d_n-1)}{365}\right) + 0{,}00128SEN\left(\frac{2\pi(d_n-1)}{365}\right) + 0{,}000719COS\left(2\left(\frac{2\pi(d_n-1)}{365}\right)\right) + 0{,}000077SEN\left(2\left(\frac{2\pi\,(d_n-1)}{365}\right)\right) \quad (10)$$

Monthly average of daily radiation ($\overline{H}$) on the horizontal surface was calculated using experimental measurements of radiation with PCE-SPM 1 radiometer and time of sunshine. Subsequently, equation 11 (linear model of Angstrom-Prescott) was used to simulate solar radiation of every day of the year 2012;and finally, the monthly average of daily radiation was calculated.The linear model of Angstrom-Prescott [25]was used to calculate the diary solar radiation (*H*) on a horizontal surface during different days of year.

$$\frac{H}{H_0} = a + b\frac{\bar{n}}{N} \quad (11)$$

where$\bar{n}$ is the number of sunshine hours; N is the astronomical daylength; a and b are parameters, which can be calculated by fitting of experimental data. Astronomical daylength (N) is the duration in hours from sunrise to sunset, and this is calculated with equation 12.

$$N = \frac{2}{15}\omega_S \quad (12)$$

2.1 Solar panel efficiency

There are factors, such as environmental temperature and wind that affect the solar panel efficiency. This is calculated with equation 13 [26], which depends of the module temperature (T_C).

$$\eta_C = \eta_{T_{Ref}}\left[1 - \beta_{ref}\left(T_C - T_{ref}\right)\right](13)$$

where$\eta_{T_{Ref}}$ is the solar panel efficiency in the reference temperature given by manufacturer; β_{ref} is the temperature coefficient; T_C is the module temperature; $T_{ref}$is the reference temperature. β_{ref} and T_C were calculated using equation 14.

$$\beta_{ref} = \frac{1}{T_0 - T_{ref}}(14)$$

where$T_0$is the temperature in zero efficiency of solar panel, for solar panel of crystalline silica is 270°C[26].

2.2 Energy balance to calculate the solar panel temperature (Tc)

Energy balance in steady state on the solar panel was carried out. Loss by radiation and forced convection were considered. Furthermore, the effect of wind on the solar panel temperature was also considered as shown in Figure 1. This energy balance relates the ambient temperature and solar panel temperature as indicated in equation 15.

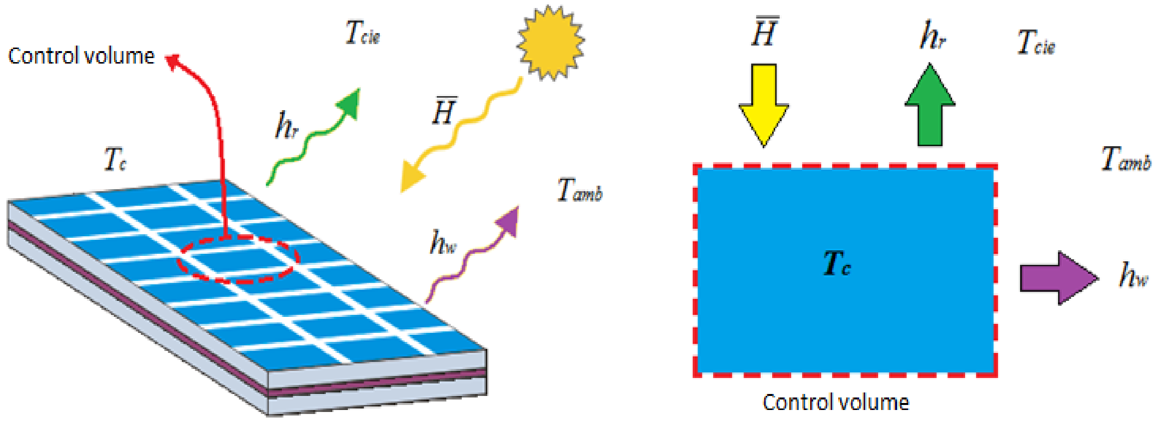

Figure 1. Control volume on the solar panel

$$\overline{H}\alpha - h_r(T_c - T_{cie}) - h_w(T_c - T_{amb}) = 0 \qquad eq.15$$

where $\overline{H}$is the solar radiation, α is the material absorptivity, $h_r$is the coefficient of radioactive exchange,T_c is the solar panel temperature, T_{cie}effective sky temperature, $h_w$is the convection coefficient due to windas expressed in equation 16and T_{amb}ambient temperature.

$$h_w = 9{,}42 + 3{,}68\ v \qquad eq.16$$

where$v$ is the average wind speed obtained from whether station 800220 (SKCG).

2.3 Validation of solar panel temperature

To validate the solar panel temperature obtained from equation 15, was used the equation 17 ([27].

$$T_C = T_{mod} = T_{amb} + \frac{G}{U_0 + U_1 v} (17)$$

where$T_{amb}$is the ambient temperature, G is the solar radiation on the plane, U_0 (W/°Cm^2) is a coefficient that describes the effect of radiation on the solar panel temperature, and U_1 (Ws/Cm^3) describes the cooling by the wind, and v is the wind speed (m/s). The equation 11 (Angström-Prescott equation) and equation 13 were replaced in equation 1 to obtain the equation 18 and to calculate the electrical potential.

$$E_p = \frac{\left[H_0\left(a + b\frac{\bar{n}}{N}\right)\right] P_{pmp}\left[\eta_{T_{Ref}}[1 - \beta_{ref}(T_C - T_{ref})]\right]}{H_{CEM}} \qquad (18)$$

Finally, T_c was obtained from equation 15 and it was replaced in equation 18 to obtain equation 19.

$$E_p = \frac{\left[H_0\left(a + b\frac{\bar{n}}{N}\right)\right] P_{pmp}\left[\eta_{T_{Ref}}\left[1 - \beta_{ref}\left(\left(\frac{\overline{H}\alpha + h_r T_{cie} + h_w T_{amb}}{(h_r + h_w)}\right) - T_{ref}\right)\right]\right]}{H_{CEM}} \qquad (19)$$

3. Conclusions

Mathematical model was developed to determine the effect of ambient temperature on the efficiency of solar panel. Generally, high temperature decreases the yield of energy production of solar panels, which becomes an important aspect for considering when you want to install solar panels in regions where high temperatures are reached.Furthermore, the solar panel temperature calculated from energy balancewill be compared with the temperature obtained from the equation of Koehl.

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