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SOLAR COLLECTOR PROJECT : EFFECT OF BRAZILIAN LOCATIONS ON THE WEEKLY PERFORMANCE

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Abstract. *In this work we investigate numerically the effect of different Brazilian geographical locations on the results of the project selection procedure for a solar collector. The collector type is plane with geometrical e physical caracteristics similar to existent in Brazilian market. The hot water demand is also typical. Whenever the collector does not supply the demand an auxiliary source is employed. The hourly diffuse radiation is calculated by breaking the total hourly horizontal radiation into beam and diffuse components using Erbs correlation. The estimation of incident and absorbed solar radiation is done by the use of the isotropic sky model. Our results points the effect of climatic data (solar radiation and dry bulb temperature) on the storage tank temperature and in the most feasible collector area.*

Keywords: *solar energy systems, engineering design, renewable energy*

1. INTRODUCTION

In the 20th century, industrial scale production of solar collector systems wide spread across the globe. However, in Brazil, the technology remains not accessible to all groups in the society. It is expected that future electricity shortages could revert this tendency.

In this paper, we examine a project methodology for solar collector system based on a typical demand. Figure 1 depicts the solar collector system. The net solar energy from the collector is used to heat the storage water to an adequate temperature at the hot-water outlet. Whenever the net solar energy is not enough an auxiliary heater is used. A more detailed analysis of the system will be effected in section 2.

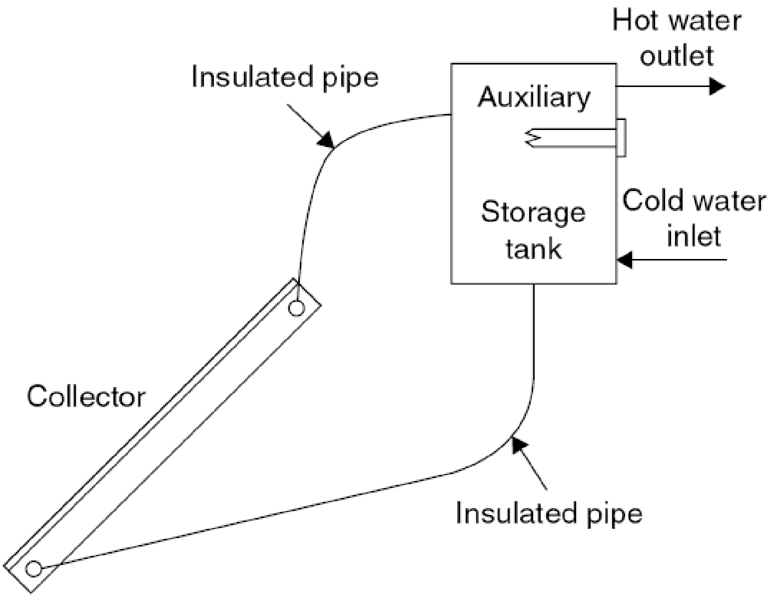

Figure 1. Schematic for a typical solar collector system

2. BASIC EQUATIONS AND METHODOLOGY

All equations will be provided in a stepwise line:

$$\delta = 23.45 \sin\left(360\frac{284+n}{365}\right) \tag{1}$$

In Eqs. (1) , δ is the sun declination in degrees from Cooper (1969), n is the day of the year ($1 \le n \le 365$),

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$$I_o = 4.92\left(1 + 0.033\cos\left[\frac{360\ n}{365}\right]\right)\times\left(\cos[\phi]\cos[\delta]\sin[\omega]+\sin[\phi]\sin[\delta]\right) \qquad (2)$$

$$k_T = \frac{I}{I_o} \qquad (3)$$

In Eqs. (2) and (3), I_o is the hourly extraterrestrial solar radiation in MJ/m^2 on a horizontal surface for the hour angle ω central to the hour, ϕ is the location latitude in degrees. k_T is the hour clearness index. The terrestrial horizontal radiation I for the hour is obtained from the automatic stations of the Brazilian National Institute of Meteorology (INMET, 2013).

The ratio of diffuse to total radiation on a horizontal surface is obtained from Erbs correlation (Erbs, 1982) given in eq. (4)

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09\, k_T & \text{for } k_T \le 0.22 \\ 0.9511 - 0.1604\, k_T + 4.388\, k_T^2 & \\ \quad - 16.638\, k_T^3 + 12.336\, k_T^4 & \text{for } 0.22 < k_T \le 0.8 \\ 0.65 & \text{for } k_T \le 0.22 \end{cases} \qquad (4)$$

Once, the ratio I_d/I is obtained, the beam component, I_b, and diffuse component, I_d, is obtained from Eq. (5)

$$I_b = I\left(1 - \frac{I_d}{I}\right) \qquad (5)$$

$$I_d = I\left(\frac{I_d}{I}\right) \qquad (6)$$

$$R_b = \frac{\cos(\phi+\beta)\cos(\delta)\cos(\omega)+\sin(\phi+\beta)\sin(\delta)}{\cos(\phi)\cos(\delta)\cos(\omega)+\sin(\phi)\sin(\delta)} \qquad (7)$$

In Eq. (7), R_b is a geometric factor corresponding to the ratio of beam radiation on the tilted surface to that on a horizontal surface. In this study we considered the collector facing the north, i.e., the surface azimuth is 180 degrees (measured clockwise from south) and β is the collector tilt angle measured from the horizontal.

From the isotropic sky model of solar radiation (Duffie and Beckman, 2006) for a tilted surface: the beam, I_{bT}; the diffuse, I_{dT}; the ground reflected, I_{gT}; and total I_T are given by Eqs. (8), (9), (10) and (11):

$$I_{bT} = I_b R_b \qquad (8)$$

$$I_{dT} = I_d\left[\frac{1+\cos(\beta)}{2}\right] \qquad (9)$$

$$I_{gT} = \rho_g I\left[\frac{1-\cos(\beta)}{2}\right] \qquad (10)$$

$$I_T = I_{bT} + I_{dT} + I_{gT} \qquad (11)$$

In Eq. (10) , ρ_g is the terrain albedo.

The absorbed solar radiation for the collector plate is given by :

$$S = I_{bT}(\tau\alpha)_b + I_{dT}(\tau\alpha)_d + I_{gT}(\tau\alpha)_g \qquad (12)$$

Where the $\tau\alpha$ terms are obtained by :

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$$\left(\tau\alpha\right)_b = \left(\tau\alpha\right)_n \left.\frac{\left(\tau\alpha\right)}{\left(\tau\alpha\right)_n}\right|_b \tag{13}$$

$$\left(\tau\alpha\right)_d = \left(\tau\alpha\right)_n \left.\frac{\left(\tau\alpha\right)}{\left(\tau\alpha\right)_n}\right|_d \tag{14}$$

$$\left(\tau\alpha\right)_g = \left(\tau\alpha\right)_n \left.\frac{\left(\tau\alpha\right)}{\left(\tau\alpha\right)_n}\right|_g \tag{15}$$

$\left(\tau\alpha\right)_n$ is a collector parameter available from the manufacturer. The ratios $\left.\frac{\left(\tau\alpha\right)}{\left(\tau\alpha\right)_n}\right|_d$, $\left.\frac{\left(\tau\alpha\right)}{\left(\tau\alpha\right)_n}\right|_g$ are function of surface slope following Brandemuehl and Beckman (1980). By his turn, the term $\left.\frac{\left(\tau\alpha\right)}{\left(\tau\alpha\right)_n}\right|_b$ depends on the beam incidence angle, cover and absorber material.

In Eq. (16), F_R is collector heat removal factor, is the ratio of the actual useful energy gain of a collector to the useful gain if the whole surface collector were at fluid inlet temperature. $F^{'}$ collector efficiency factor, represents the ratio of the actual useful energy gain to useful gain that would result if the collector absorbing surface had been at the local fluid temperature. U_L is the collector global heat transfer coefficient in W/(m^2 C), $\dot{m}_c$ is the collector fluid flow rate per area in kg/(s m^2), c_p is the collector fluid specific heat at constant pressure evaluated at the ambient temperature.

$$F_R = \frac{\dot{m}_c\ c_p}{U_L}\left[1 - \exp\left(-\frac{F^{'}U_L}{\dot{m}_c\ c_p}\right)\right] \tag{16}$$

In Eq. (17), Q_u is the useful energy delivered from the collector to the storage tank. The max functions indicates, whenever the absorbed energy is greater than the heat transfer loss, energy is transferred from the collector frame to the storage tank.

$$Q_u = \max\left[0, A_c F_R\left(S - U_L\left[T_{tank} - T_a\right]\right)\right] \tag{17}$$

In the above equation, A_c is the collector area and T_a is the ambient temperature where the collector is located. Also, the storage tank temperature, T_{tank}, is assumed homogeneous in all the tank.

Equation (18) represents the tank heat loss for the environment. Its is assumed that the $T_a^{'}$, the ambient temperature where the tank is located can be different.

$$Q_{loss,tank} = U_{L,tank} A_{tank}\left[T_{tank} - T_a^{'}\right] \tag{18}$$

In Eq. (19) the L_{max} is the projected load based on a minimum hot water supply temperature T_{min} . It is assumed the makeup water temperature to the tank T_{mains} is kept constant.

$$L_{max} = \dot{m}_L c_p\ \left[T_{min} - T_{mains}\right] \tag{19}$$

From the previous equation the energy required from the load Q_{load} in a given hour is calculated from Eq. (20). OnOff is a 24 position vector corresponding to a 24 h period. When a given position is the value 1, the hot water load at T_{min} or above is required. The value 0, implies hot water is not required.

$$Q_{load} = \mathrm{OnOff}\ \min\left[L_{max}, \dot{m}_L c_p\ \left[T_{tank} - T_{mains}\right]\right] \tag{20}$$

In the previous equation, whenever the storage temperature is less than T_{min}, the auxiliary energy source supplies sufficient energy to heat the water coming from the storage tank to T_{min}.

Eq. (21) is based on the energy balance for the storage tank. The superscript n correspond to the current hour, and n -1 to the previous hour.

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$$T_{tank}^{n} = T_{tank}^{n-1} + \frac{Q_u - Q_{loss,tank} - Q_{load}}{m_{tank} c_p} \quad (21)$$

The calculation procedure for a project consists in solving equations (1) to (21) for each hour. A example of calculation is depicted in the next section.

When the calculation is performed for a week, the weekly fraction of the minimum load supplied from the solar collector system F_{week} is obtained from :

$$F_{week} = \frac{\sum_{n=1}^{N_{hours,week}} Q_{load}}{7\, N_{hours}\, L_{max}} \quad (22)$$

The variable N_{hours} represents the number of hours the hot water is required each day. $N_{hours,week}$ is the number of hours of the week.

3. RESULTS AND DISCUSSION

The calculation procedure described in the previous section was implemented for calculating the needed collector area A_c of a typical north facing plane solar collector system such as the one depicted in Figure 1, using the thermodynamics software EES (Klein, 1993), for different Brazilian cities. The analysis was performed for seven Brazilian cities, namely: Manaus, Fortaleza, Rio de Janeiro, São Paulo, Florianopolis. The corresponding latitudes in degrees from the equator for the previous cities are given by the vector [-3,-3.7,-22.9,-23.5,-27.6,-30].

In Table 1 is presented fixed properties of the solar collector system and load demand. The parameters β, U_L, $(\tau\alpha)_n$, $\dot{m}_c$, $F^{'}$ are collector parameters. The storage tank parameters are m_{tank}/A_c, $U_{L,tank}$, $(H/D)_{tank}$. The load parameters are T_{mains}, T_{min}, $\dot{m}_L$, F_{week}. The load is uniformly distributed over the day from 7 AM to 9 PM, i.e, the vector OnOff is [0, 0, 0, 0, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 0, 0].

Table 1. Baseline parameters.

Parameter	Value
β	40^o
U_L	$4\ W/(m^2\ C)$
$(\tau\alpha)_n$	0.77
$\dot{m}_c$	$50\ kg/(m^2h)$
$F^{'}$	0.95
ρ_g	0.2
$T_a^{'}$	21 C
m_{tank}/A_c	$60\ kg/m^2$
$U_{L,tank}$	$1.05\ W/(m^2\ C)$
$(H/D)_{tank}$	3
T_{mains}	25 C
T_{min}	45 C
$\dot{m}_L$	12.86 kg/h
F_{week}	0.75

The climate data for performing the calculations were obtained from the INMET automatic stations from 01/28/2013 to 02/03/2013. The following values were used: I, the total hour solar radiation incident on a horizontal surface, and T_a, the hourly averaged ambient temperature. Those values are depicted in Figs. 2 and 3 for the week considered for the project calculation.

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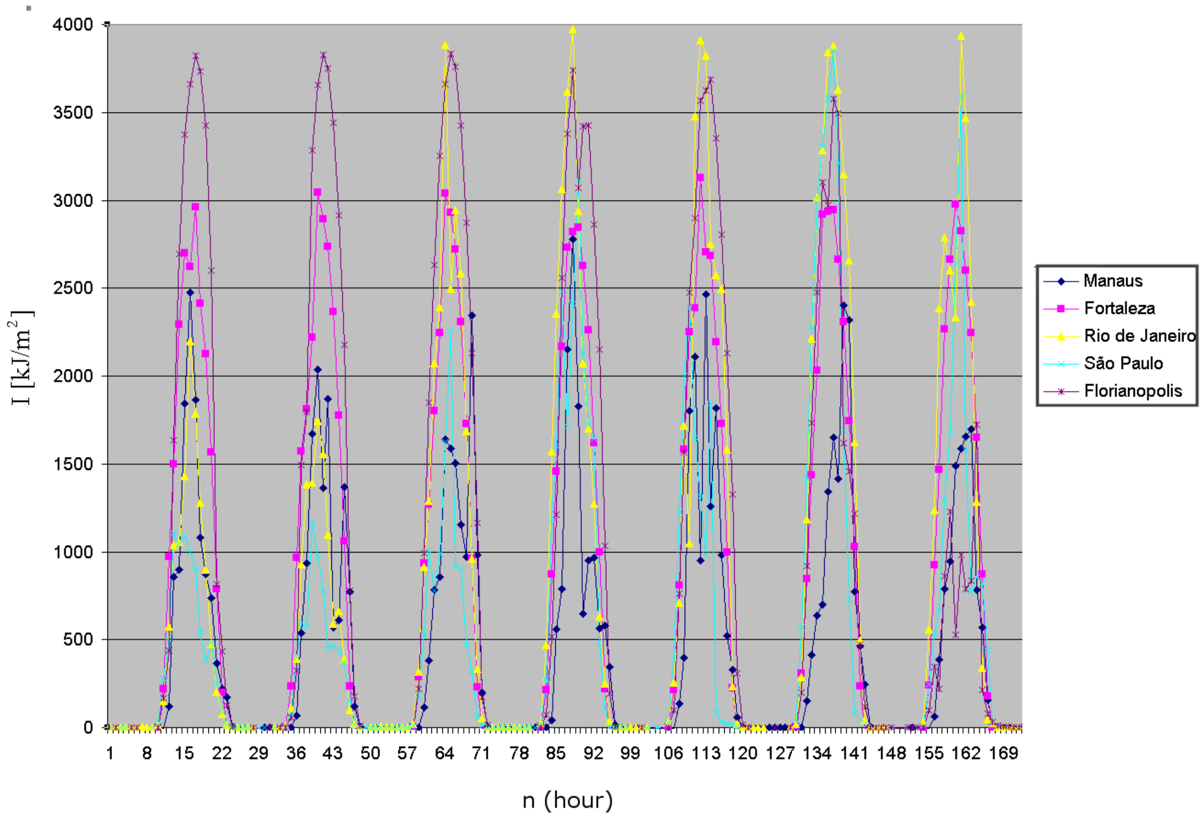

Figure 2 – Hour terrestrial horizontal radiation.

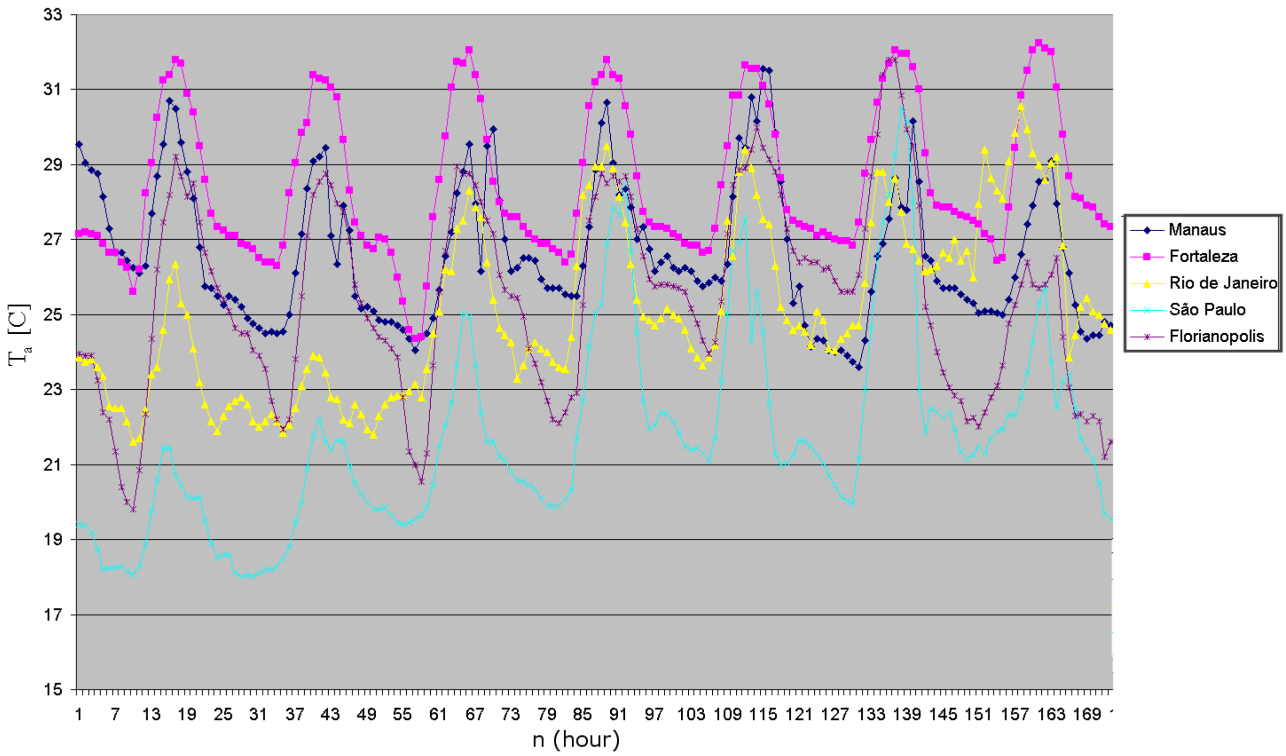

Figure 3. Hour temperature data for different locations

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The solution is obtained iteratively by trial and error. It is necessary to guess both the collector area A_c and the initial tank temperature and see if the desired F_{week} is reached and if a steady periodic solution is reached for the tank temperature, i.e., the final tank temperature equal to the initial temperature. Table 2 shows the results obtained for the collector area. The greatest required area was for Manaus, whereas Florianopolis requires the smallest. The results correlate well with the number of peak levels in Fig. 2, i.e., cities with more peak solar intensities closer to the maximum result in a lower required area. By his turn, from Eq. (17), lower air temperatures reduce the useful delivered solar energy to the load, increasing the required area. From Fig. 3, although Fortaleza and Manaus had the greatest air temperature profile for the week, the solar radiation profile was inferior to Florianopolis and Rio de Janeiro. In this sense, the results point to more sensitivity of collector area to the solar intensity than air temperature. It is also worthwhile to mention a basic premise of the simulation is that the week is a representative sample of the season during which the load is required.

Table 2. Collector Area

City	A_c [m^2]
Manaus	5
Fortaleza	2.2
Rio de Janeiro	1.9
Sao Paulo	3.8
Florianopolis	1.2

4. CONCLUSION

A calculation procedure for specifying the size of collector of a typical solar system was presented. Week data for 5 different Brazilian cities were used. The results point to more sensitivity of the collector area to the solar radiation intensity profile than ambient temperature.

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