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A COMPARISON BETWEEN TRACKING AND FIXED FLAT PLATE SOLAR COLLECTORS

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Abstract. *The continuous research for an alternative power source due to the perceived scarcity of fuel fossils made the use of solar energy in recent years reach a remarkable edge. It is a clean and renewable energy source. Nevertheless, the Earth's daily and seasonal movement affects the intensity of the solar radiation incident on devices that use this energy source. The devices can track the sun in order to ensure an optimum position regarding the incident solar radiation, maximizing the absorbed solar energy. According to the motion of the tracking system, the goal might be the total energy absorbed during a period of one year or in a critical period of the year, e.g., the winter. The main goal of this paper was to develop a mathematical model to evaluate the general behavior of a flat plate solar collector, for different tracking systems. It was observed that the full tracking system with rotation about two axes showed the higher absorbed energy, when compared to the rotation about a single axe and to a fixed collector.*

Keywords: *flat plate solar collectors, sun tracking, mathematical model*

1. INTRODUCTION

Energy is essential for the economic growth and social development of any country. The quality of life is closely related to energy consumption, which is continuously increasing in the last few decades in developing countries. The result is that the energy demand is increasing and it cannot be supplied by the traditional energetic technology. Besides, there is a connection between the energy consumption and the environmental impacts. The world's total primary energy supply is essentially based on fossil sources, as shown by IEA (2011a). In 1973, the renewable sources were responsible for 12.5% of the total, and in 2009, for 13.3%. Therefore, finding clean sources of energy to satisfy the world's growing demand is one of society's foremost challenges for the next half-century.

Solar energy is a clean, renewable, abundant and cheap source of energy. Solar heating technologies use solar energy to provide heat. Collectors can be designed to provide heated water at a household scale, but the technology is also being increasingly employed at larger scale to provide hot water for commercial and industrial operations or linked to district heating installations (IEA, 2011b). A flat plate collector is the simplest means available for solar energy utilization. Flat plate collectors can be designed for applications requiring energy delivery at moderate temperatures, up to perhaps 100°C above ambient temperature (Duffie and Beckman, 2006). The solar thermal collector capacity in operation worldwide at the end of 2009 equaled 172.4 GW_{th}. Between 2004 and 2009, the annually installed glazed water collector area worldwide has almost tripled, and the worldwide average annual growth rate between 2000 and 2009 was 20.8% (IEA, 2011a). According to ABRAVA data, in 2010 the Brazilian production of solar collectors increased 21.1% above 2008, achieving 6.2×10^6 m^2.

The amount of energy absorbed by a solar collector plays an important role in sizing and optimizing solar systems. The performance of a flat plate solar collector is highly influenced by its orientation and tilt with the horizontal. It is important to know what the optimum tilt and azimuth angles are at which to mount a fixed collector on a flat roof or on the ground such that it receives maximum irradiation (Lave and Kleissl, 2011). The diurnal and seasonal movement of Earth affects the radiation intensity on the solar systems. The diurnal and seasonal movement of earth affects the radiation intensity on the solar systems. Sun trackers move the solar systems to compensate for these motions, keeping the best orientation relative to the sun (Mousazadeh et al., 2009).

Mousazadeh et al (2009) describe different types of sun-tracking systems and discuss their cons and pros. Solar tracking can be implemented by using one-axis, and for higher accuracy, two-axis sun-tracking systems. For a two-axis sun-tracking system, two types are known: polar (equatorial) tracking and azimuth/elevation (altitude–azimuth) tracking. Sun-tracking systems are usually classified into two categories: passive (mechanical) and active (electrical) trackers.

Although the use of sun tracking systems can be applied to both flat plate solar collectors and PV cells, it is more common to find literature related to PV systems. During the last few years, photovoltaic solar systems have become one of the most popular renewable energy sources. Nevertheless, the high cost of these installations in relation to the generated electricity constitutes one of the main drawbacks of this technology. In this sense, one and two axes solar tracking systems seems to be an attractive alternative compared to those fixed systems since they make it possible to maximize the capture of solar energy (Cruz-Peragón et al., 2011).

Tomson (2008) evaluated the improved solar energy yield by simplified tracking. In the paper, it was described mainly the performance of PV modules with daily two-positional tracking. The symmetrical and asymmetrical positions about the north–south axis were analyzed, corresponding to the positions of sun in the morning and in the afternoon. The tracking drive is simple and requires a minimum energy input during the brief daily triggering of movement. Results indicated that two-positional exposure guarantees always a gain, as compared to the fixed collector in the optimal position. The seasonal energy yield was increased by 10–20% over the yield from a fixed south-facing collector tilted at an optimal angle. The results were based on long-term solar data measured in Estonia.

Sefa, Demirtas and Çolak (2009) describe the design and application of a novel one-axis sun tracking system, which follows the position of the sun and allows investigating effects of one-axis tracking system on the solar energy in Turkey. The system was designed to obtain electrical energy from sun and to connect the system in parallel with the grid. It consisted on 2500W solar panels, with 2500W total power and 3500 kg total weight. The system has been applied as one axis because of facing control difficulties of two axes control with huge mechanical body. The results showed that the solar energy collected on the tracking system is considerably much efficient than the fixed system. The tracking system developed in this study provides easy installation, simple mechanism and less maintenance.

The parameters that best reflect the performance of a PV system are the energy production and the performance ratio. The energy production reflects the ability of a PV system to generate energy. The performance ratio excludes the influence of irradiation capturing ability, and simply reflects how well the captured irradiation can be converted to electricity. Gomez-Gila, Wang and Barnett (2012) compared the energy production of four photovoltaic system configurations: fixed, 1-axis and 2-axis tracking flat plate, and concentrating photovoltaics (CPV). The energy production comparison was based on real performance data from systems installed in Spain in 2009. Compared with the fixed flat plate systems, 1-axis and 2-axis tracking flat plate systems have 22.3% and 25.2% gain in the annual energy production, respectively. The energy production from CPV systems is quite close to that from fixed flat plate systems. The performance ratio was estimated from the best available irradiation data, and the analysis showed that the performance ratio decreases in the order: fixed, 1-axis, 2-axis tracking flat plate, CPV.

Cruz-Peragón et al. (2011) quantified the additional solar gain of tracking system respect to fixed devices to demonstrate their economical viability in Spain. The authors demonstrated that two-axes tracking systems can assure an economic viability respect to fixed ones in most of the Spanish national territory. Nevertheless, there are some areas where high humidity, rainfall and latitude combine making these solutions not recommendable.

Lave and Kleissl (2011) determined optimum tilt and azimuth angles for solar panels for the continental United States, using the Page Model applied to the SUNY 10-km gridded data. The yearly global irradiation incident on a panel at this optimum orientation was compared to the solar radiation received by a flat horizontal panel and a 2-axis tracking panel. Compared to global horizontal irradiation, irradiation at optimum fixed tilt increased with increasing latitude. Irradiation incident on a 2-axis tracking panel in one year was 25%-45% higher than irradiation received by a panel at optimum fixed orientation. Contrary to the literature suggestions, it was found for most locations higher global irradiation levels could be obtained by deviating from this rule. The optimum tilt was never greater than latitude tilt, but up to 10° less than latitude tilt. On average, the deviation from latitude tilt increased at higher latitudes, but optimum tilt was not found to simply be a function of latitude. Seasonal weather patterns such as winter clouds led to changes in the optimum tilt.

Eke and Senturk (2012) studied the performance of two double axis sun tracking photovoltaic systems. The performance measurements of the PV systems were carried out first when the PV systems were in a fixed position and then the PV systems were controlled while tracking the sun in two axis and the necessary measurements were performed. It is calculated that 30.79% more PV electricity is obtained in the double axis sun-tracking system when compared to the latitude tilt fixed system. Measured data of the PV systems were also compared with simulated data, with differences between simulated and measured energy values less than 5%.

The purpose of the current work was to quantify the additional energy absorbed by a flat plate solar collector with sun tracking respect to fixed devices. Hourly results have been integrated over the year, obtaining annual results. The analysis can be extended to other cities, altering only a few parameters.

2. MATHEMATICAL MODEL

The equations set presented in the mathematical model were developed according to Duffie and Beckman (2006) model. In order to study the influence of tilt angle, the performance of a flat plate collector was determined, based on an energy balance that indicates the distribution of incident solar energy into useful energy gain, thermal and optical losses.

The collection efficiency of a flat plate solar collector is defined as the ratio of the useful gain over some specified period to the incident solar energy over the same period. In this paper, the time period considered was 1 day:

$$\eta = \frac{\int Q_u \, dt}{A_c \int G_T \, dt} \tag{1}$$

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G_T is the incident solar radiation. Q_u represents the useful energy output of a collector of area A_c, given by:

$$Q_u = A_c \left[S - U_L \left(T_{pm} - T_a\right)\right] \tag{2}$$

S is the solar radiation absorbed by the collector, U_L is the collector overall loss coefficient and T_{pm} and T_a represent the mean absorber plate temperature and the ambient temperature, respectively. The collector overall loss coefficient is the sum of the top, bottom and edge loss coefficients,

$$U_L = U_t + U_b + U_e \tag{3}$$

The top loss coefficient U_t takes into account convection and radiation thermal losses to the surroundings through the top of the collector. The bottom loss coefficient U_b represents convection and radiation losses to the environment through the backside and the edge loss coefficient represents the losses from the edge of the collector. The modeling of these loss coefficients is the same presented in Duffie and Beckman (2006) and it was suppressed.

The mean absorber plate temperature is solved in an iterative procedure involving the collector overall loss coefficient, as suggested by Duffie and Beckman (2006). The ambient temperature is fixed for the problem.

The absorbed solar radiation was determined on an hourly basis, assuming a isotropic sky model. The radiation was considered to include three components: beam, isotropic diffuse and solar radiation diffusely reflected from the ground:

$$S = I_b\, R_b\, (\tau\alpha)_b + I_d\, (\tau\alpha)_d \left(\frac{1+\cos\beta}{2}\right) + \rho_g\, (I_b + I_d)\, (\tau\alpha)_g \left(\frac{1-\cos\beta}{2}\right) \tag{4}$$

I_b and I_d represent the beam and diffuse components of the incident solar radiation. R_b is the geometric factor, defined as the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time. β is the slope of the collector, ρ_g is the ground reflectance, and $(\tau\alpha)_b$, $(\tau\alpha)_d$ and $(\tau\alpha)_g$ represent the transmittance-absorptance products for the beam, diffuse and ground-reflected radiation, respectively.

The transmittance-absorptance product is a property of the system. It is well known that, of the radiation passing through the cover system and incident on the plate, some is reflected back to the cover system. However, not all this radiation is lost since some of it is reflected back to the plate. There are multiple reflections of the radiation between the cover and the absorber plate, in a way that

$$(\tau\alpha) = \frac{\tau\alpha}{1 - (1-\alpha)\rho_d} \tag{5}$$

τ is the transmittance of the cover system at a given angle, α is the angular absorptance of the absorber plate, and ρ_d is the reflectance of the cover system for the diffuse radiation incident from the bottom side. These optical properties can be estimated for the materials, for given incidence angles, as presented in Duffie and Beckman (2006). The incidence angle for the beam radiation is given by the tracking system; and the incidence angles for diffuse and ground reflected radiation are given by:

$$\theta_d = 59.7 - 0.1388\beta + 0.001497\beta^2 \tag{6}$$

$$\theta_g = 90^\circ - 0.5788\beta + 0.002693\beta^2 \tag{7}$$

The geometric factor R_b is given by:

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{8}$$

θ is the incidence angle of the beam radiation, and θ_z is the zenith angle, given by:

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \mathrm{sen}\,\phi\,\mathrm{sen}\omega \tag{9}$$

ϕ is the latitude, δ is the declination and ω is the hour angle.

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The efficiency of the collector and the absorbed solar radiation were determined for a period of one day, on an hourly basis. The hourly radiation was estimated from daily data. It was defined an average day for each month of the year, and the results were obtained for this day. It was assumed to represent the whole month; therefore, the solar radiation obtained for the day was multiplied for the number of days of the month. The procedure was repeated for the other months and the solar radiation for one year could be determined.

The solarimetric data used in this paper refer to the monthly averaged solar radiation for Belo Horizonte, obtained in Guimarães (1995), presented in Table 1. The clearness index K_T represents the ratio of the solar radiation and the extraterrestrial radiation H_o for the day,

$$K_T = \frac{H}{H_o} \tag{10}$$

The extraterrestrial radiation H_o is determined by:

$$H_o = \frac{24*3600\,G_{sc}}{\pi}\left[1+0,033\cos\left(\frac{360^\circ\ n}{365}\right)\right]\left(\cos\phi\cos\delta\ \text{sen}\omega_s + \frac{\pi\omega_s}{180^\circ}\text{sen}\phi\,\text{sen}\delta\right) \tag{11}$$

G_{sc} is the solar constant, G_{sc} = 1367 W/m^2. n is the nth day of the year and ω_s is the sunset hour angle.

Table 1. Clearness index for Belo Horizonte (Guimarães, 1995)

Month	**K_T**
January	0,46
February	0,45
March	0,51
April	0,53
May	0,55
June	0,60
July	0,64
August	0,53
September	0,48
October	0,50
November	0,45
December	0,41

The hourly solar radiation estimation from daily solar radiation is based on the methodology proposed by Collares-Pereira and Rabl (1979). The ratio of hourly total to daily total radiation is

$$r_t = \frac{I}{H} \tag{10}$$

where

$$r_t = \frac{\pi}{24}(a + b\cos\omega)\frac{\cos\omega - \cos\omega_s}{\text{sen}\,\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \tag{11}$$

$$\begin{aligned} a &= 0.409 + 0.5016\,\text{sen}(\omega_s - 60) \\ b &= 0.6609 - 0.4767\,\text{sen}(\omega_s - 60) \end{aligned} \tag{12}$$

The ratio of hourly diffuse to daily diffuse radiation is

$$r_d = \frac{I_d}{H_d} \tag{13}$$

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$$r_d = \frac{\pi}{24}\frac{\cos\omega - \cos\omega_s}{\text{sen}\,\omega_s - \frac{\pi\omega_s}{180}\cos\omega_s} \tag{14}$$

The distribution of monthly average daily radiation into its beam and diffuse components is obtained by Collares-Pereira and Rabl (1979) correlation:

$$\frac{H_d}{H} = \begin{cases} 0{,}99 & \text{for } K_T \le 0{,}17 \\ 1{,}188 - 2{,}272K_T + 9{,}473K_T^2 - 21{,}865K_T^3 + 14{,}648K_T^4 & \text{for } 0{,}17 < K_T \le 0{,}75 \\ -0{,}54K_T + 0{,}632 & \text{for } 0{,}75 < K_T < 0{,}8 \\ 0{,}2 & \text{for } K_T \ge 0{,}8 \end{cases} \tag{15}$$

Since the useful gain of a flat plate solar collector is proportional to the amount of solar radiation reaching the surface and to the solar radiation absorbed, it is important to maximize absorption of solar radiation. Some collectors track the sun by moving in prescribed ways to minimize the angle of incidence of beam radiation on their surfaces and thus maximize the incident beam direction. Regarding movement capability, sun-tracking systems are designed to track the sun on a single axis, according to the azimuth angle or to track the sun on both axis, according to the azimuth and solar altitude angles (Eke and Santurk, 2012).

Five types of tracking were evaluated:

R1) a plane rotated about a horizontal east-west axis with continuous adjustment to minimize the angle of incidence;

R2) a plane rotated about a horizontal north-south axis with continuous adjustment to minimize the angle of incidence;

R3) a plane with a fixed slope rotated about a vertical axis. In this case, the angle of incidence is minimized when the surface azimuth and solar azimuth angles are equal;

R4) a plane with continuous tracking about two axes to minimize the angle of incidence.

These tracking movements were compared to a collector with fixed slope to the north (referred as R5) and to a horizontal collector faced to north (referred as R6). It is well known that, for maximum annual energy availability, a surface slope equal to latitude is best. For maximum summer availability, slope should be approximately 10° to 15° less than the latitude. For maximum winter availability, slope should be approximately 10° to 15° more than the latitude (Saraf and Hamad, 1988; Duffie and Beckman, 2006). Therefore, the fixed slope was taken as ϕ+10º.

3. RESULTS

In order to find the tilt angle for a typical collector (design and dimensions mentioned in Table 2, suggested by Saraf and Hamad, 1988 and Duffie and Beckman, 2006) at any particular day, the set of equations were translated into a computer routine using Matlab. This program was used to determine the hourly tilt angle, the incident solar radiation and the useful gain of the collector. The absorbed solar radiation was integrated over the day and the collector efficiency was determined at the end of the day. The day of simulation was selected as the recommended average day for each month (from Klein, 1977). The values obtained were assumed to represent all the days of the month; therefore, these values were multiplied by the number of the days of the month and the procedure was repeated for the next month, allowing the determination of the annual incident solar radiation and the annual absorbed solar radiation. The values obtained for the tracking systems were compared.

Table 2. Collector parameters

Parameter	**Value**
Absorber area	1.4 m^2
Number of glass covers	1
Cover thickness	0.0023 m
Cover extinction coefficient	16
Cover index of refraction	1.526
Tube spacing	0.1 m
Tube inner diameter	0.008 m
Absorber plate thickness	0.0045 m
Glass cover emittance	0.88
Absorptance of the plate at normal incidence	0.90
Insulation thermal conductivity	0.045 W/m.K

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The computer routine was simulated for Belo Horizonte, Brazil, with latitude of 19.92ºS. The ambient temperature was defined as the average value for Belo Horizonte from 2000 to 2009, extracted from Meteonorm, 2012. Numerical tests were carried out for a period of one year. In order to compare the climatic conditions during the year, Fig. 1 presents the theoretical number of daylight hours for the location. It can be seen that it increases during the summer and reaches its minimum value in July.

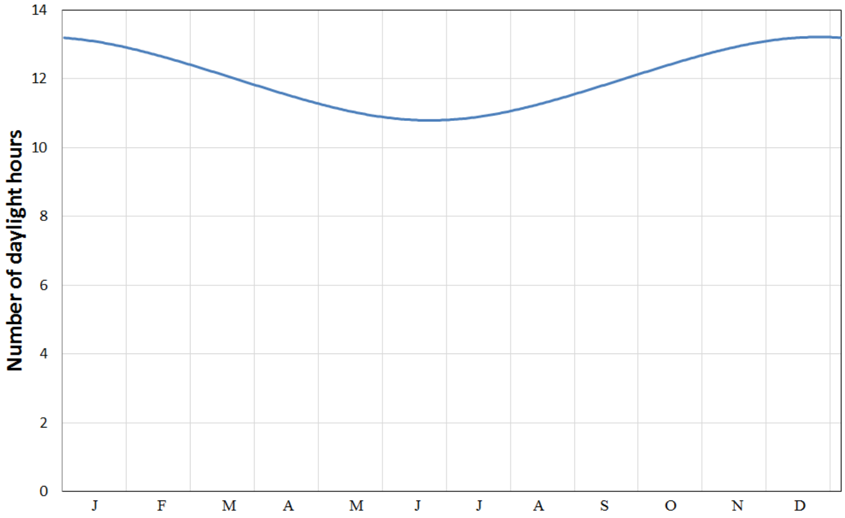

Figure 1. Number of daylight hours for Belo Horizonte

Figure 2 presents the daily extraterrestrial radiation on a horizontal surface (H_o), the average daily radiation on a horizontal surface during the year (H), obtained for Belo Horizonte, and the clearness index (K_T) used in this paper. The extraterrestrial radiation represents the radiation that would be received in the absence of atmosphere, or the theoretically possible radiation available if there were no atmosphere. It can be seen that the amplitude of H_o is significantly higher than the amplitude of H, which represents the radiation level. It can be explained by the opposite behaviors of the clearness index and the extraterrestrial radiation. Higher clearness indexes are obtained when the extraterrestrial radiation is lower.

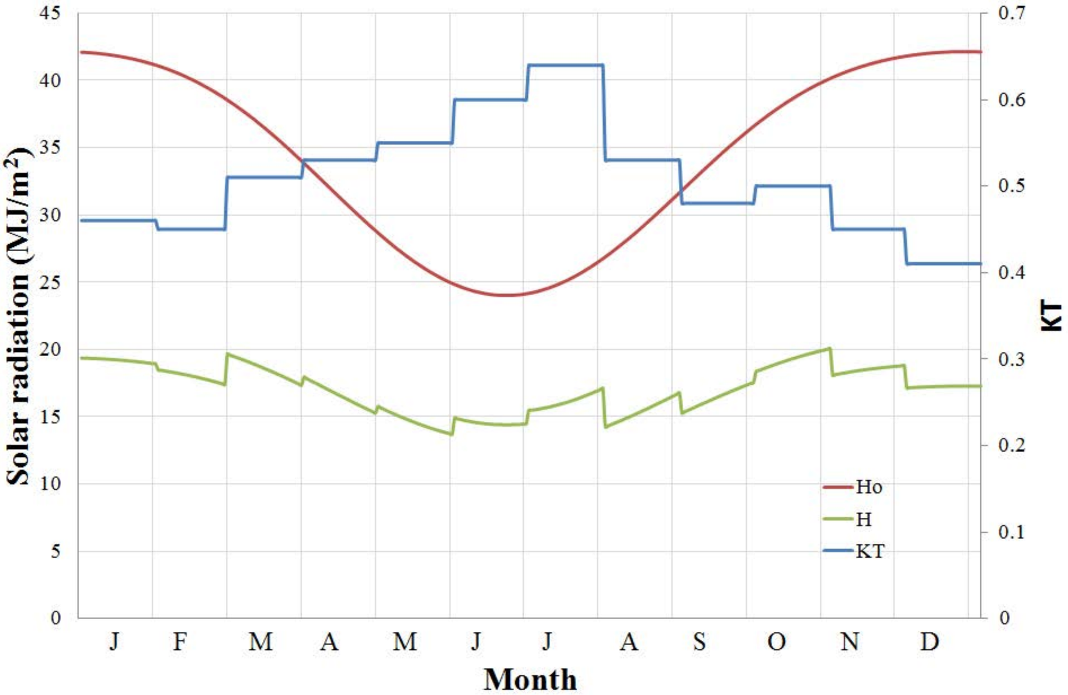

Figure 2. Extraterrestrial radiation and solar radiation for a horizontal surface

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The total useful energy output of the collector, the absorbed solar radiation and the average efficiency of the collector are shown in Table 3, for the tracking systems evaluated. It can be seen that the higher values are found for R4, which corresponds to continuous tracking about two axes, as expected. Since the incidence angle is always zero, the amount of solar energy incident on the collector is maximized, increasing the absorbed solar radiation and the efficiency of the collector. On the other hand, the lower values are found for R6, which corresponds to the collector on a horizontal position faced to north. Nevertheless, the collector efficiency does not present significant variations with the tracking system evaluated.

Table 3. Useful energy, absorbed solar radiation and collector efficiency

Tracking system	Q_u/A_c (MJ/m^2)	S (MJ/m^2)	η
R1	1.254	1.398	89.44%
R2	1.332	1.478	89.86%
R3	1.364	1.517	89.67%
R4	1.415	1.566	90.10%
R5	1.202	1.343	89.24%
R6	1.133	1.272	88.85%

The behavior of the absorbed solar radiation during the year is shown in Fig. 3. It can be seen that this parameter varies significantly during the year. For all the evaluated tracking systems, the general behavior is the same, with the maximum values found in July and the minimum values are in December. Depending on the tracking system, great differences are found. For instance, the solar radiation absorbed by a horizontal collector in July is approximately half the solar radiation absorbed by a collector with continuous tracking. Additionally, it can be seen that R4 is the tracking system with higher absorbed solar radiation and R6 is the one with lower absorbed solar radiation.

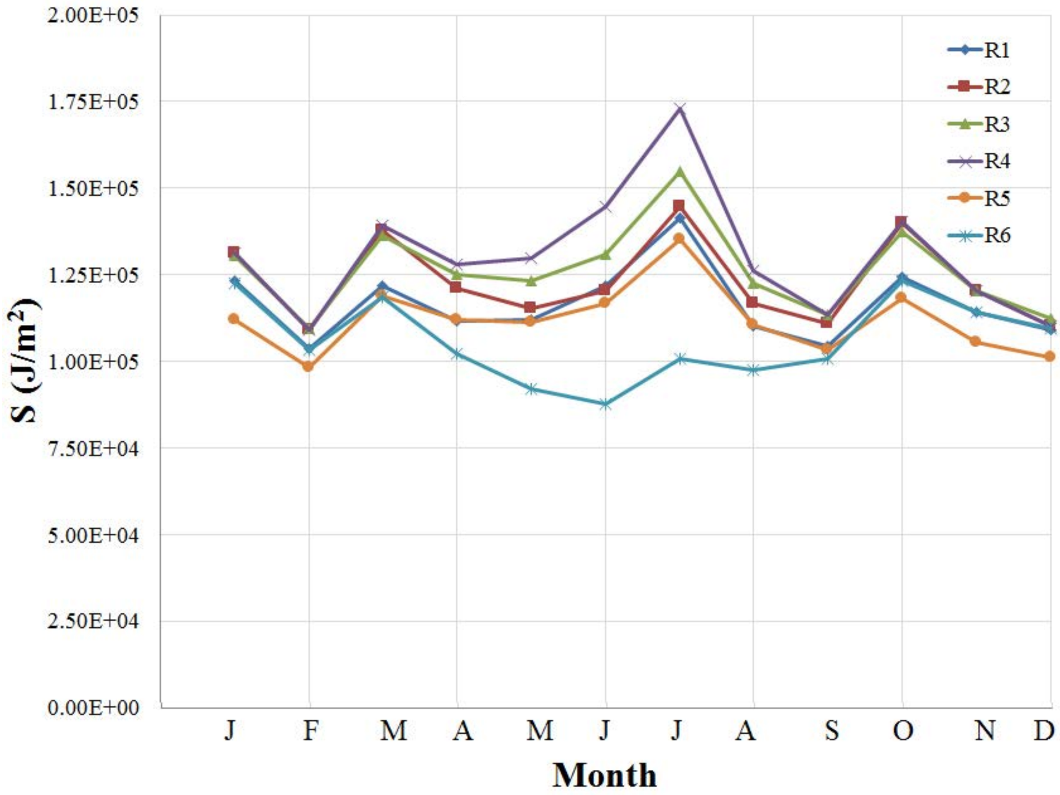

Figure 3. Absorbed solar energy

The useful energy output of the collector obtained for each month is shown in Fig. 4, as a function of the month. It can be seen that that the behavior of the useful energy is similar to the behavior of the absorbed solar radiation (Fig. 3).

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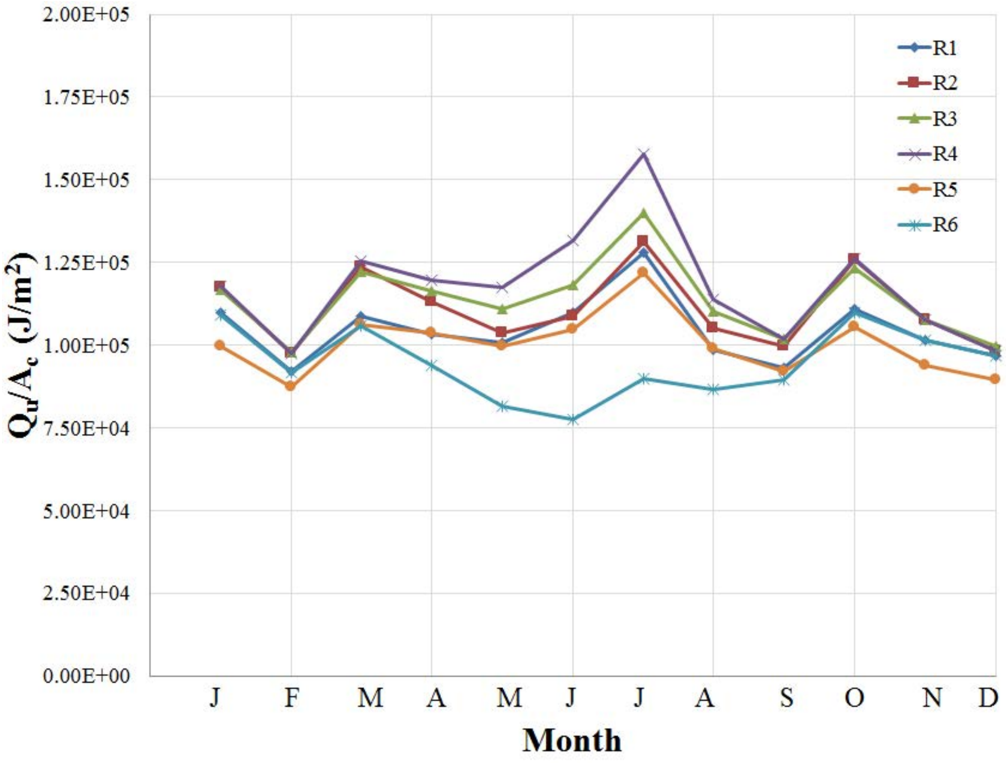

Figure 4. Useful energy output

The collector efficiency is shown in Fig. 5. The general behavior is similar to the behavior observed in Fig. 3 and 4. However, the efficiency does not vary significantly with the month or with the tracking system.

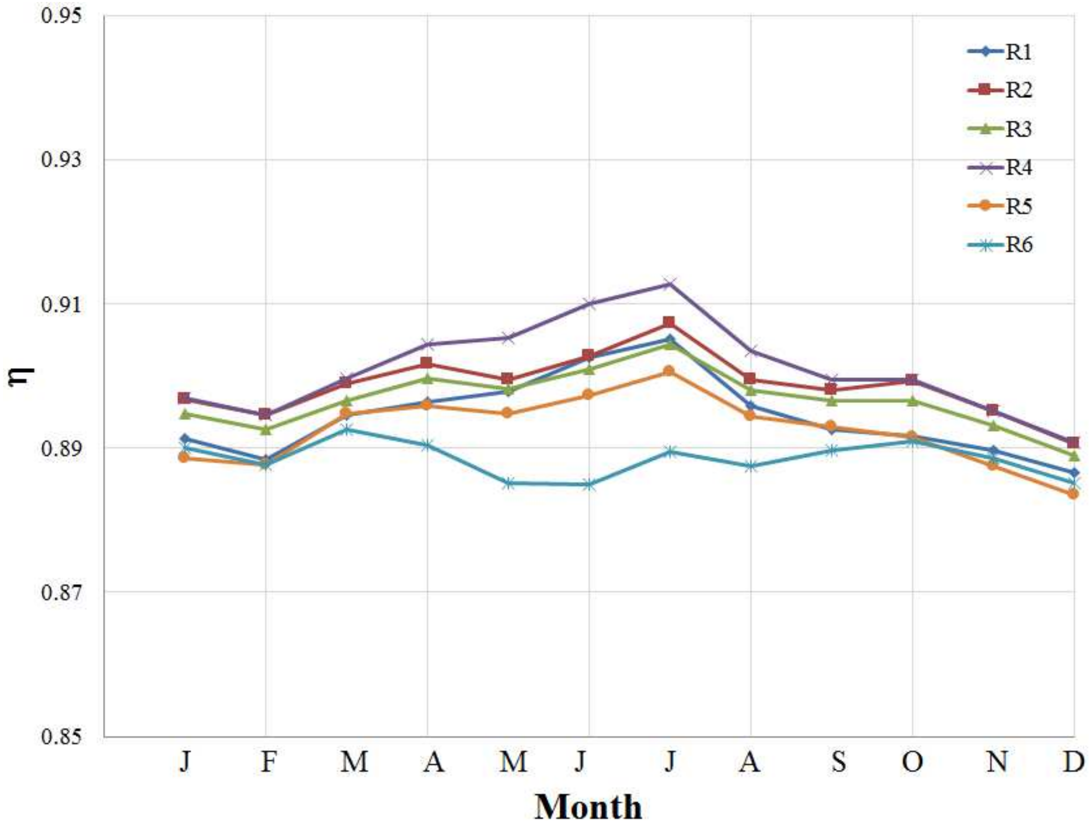

Figure 5. Collector efficiency

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For a fixed slope, it is important to define the proper value. A fixed surface slope increases the amount of incident and absorbed solar radiation in different seasons. Figure 6 presents the distribution of useful energy output and collector efficiency during the year, for a fixed slope of the collector, faced to north. Five values of slope were evaluated, related to the absolute latitude. In the figure, the lines with markers represent the useful energy, and the lines without markers represent the collector efficiency. The general behavior of the useful energy is similar to the general behavior of the collector efficiency, although with higher variations.

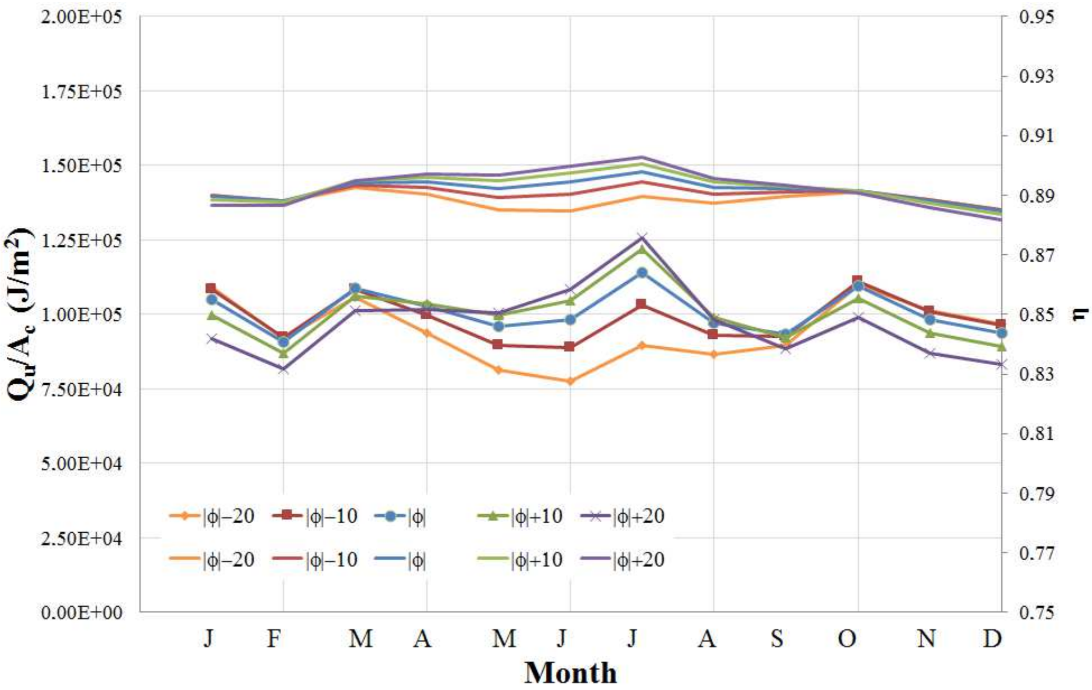

Figure 6. Useful energy output and collector efficiency for a fixed slope

Table 4. Total useful energy, absorbed solar radiation and average collector efficiency for a fixed slope

Slope	**|ϕ| - 20°**	**|ϕ| - 10°**	**|ϕ|**	**|ϕ| + 10°**	**|ϕ| + 20°**
Q_u/A_c (MJ/m²)	1.133	1.184	1.207	1.202	1.167
S (MJ/m²)	1.271	1.326	1.350	1.343	1.303
η	88.85%	89.04	89.17	89.24	89.27

It can be seen that higher slopes (greater than the latitude) result in higher values during the winter season, and lower slopes result in higher values during the summer season. However, when the total values are evaluated (Table 4), it can be seen that the higher values of incident and absorbed solar radiation are found when the slope equals the absolute latitude. The collector efficiency increases with the slope, but the differences are not significant.

4. CONCLUSIONS

In this paper, it was performed a comparison of the useful energy output, the absorbed solar radiation and the efficiency of a flat plate collector, for several tracking systems. As expected, the best behavior was observed for a continuous tracking about two axes and the worst behavior, for a horizontal collector.

The variation of the useful energy and absorbed solar radiation was more significant than the variation of the efficiency, but all the parameters presented similar performances, with higher values in July (winter) and lower values in December (summer).

For a fixed slope of a collector faced to north, it was observed that higher slopes increase the useful energy output in winter months and lower slopes increase the useful energy output in summer months. Nevertheless, the maximum total useful energy was obtained when the slope equals the absolute latitude, as described in literature. It is worth noting that the average efficiency is higher for higher slopes, but this parameter is not significantly affected by the slope, for the values studied.

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