Solar Irradiation over a Flat Surface with Different Tracking Strategies

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Abstract

The importance of solar tracking systems lies in the need to optimize the amount of solar radiation on solar collectors of different types. In this work, the monthly mean daily irradiation was analyzed on a flat surface of unitary area, under different tracking schemes of the Sun, by means of the use of a numerical model. For this purpose, solarimetric data was obtained from some stations of the new Mexican Solarimetric Network, the solar irradiance incident on a flat horizontal plate was calculated. Also, the movement of some tracking systems was carried out in steps with different time intervals in order to compare it with their respective continuous movement. It was found that stepped movements report yearly incident solar irradiation values above 98% respect to continuous movement in the widest interval.

Keywords: Solar resource assessment, solar tracking strategies, PV collectors, solar collectors

1. Introduction

The importance of solar tracking systems lies in the need to optimize the amount of solar radiation on solar collectors of different types (Yang, 2016). In particular, PV systems present significant variations in their performance depending on the optical configuration and tracking strategies used (Sumathi et al, 2017; Joshi and Arora, 2017;Fernandez-Ahumada et al, 2017; Mehleri et al, 2010; Li and Lam, 2007). The cost of tracking schemes can significantly impact overall costs depending on the complexity and precision of the mechanisms.

There are several works in literature (Sumathi et al, 2017; Yang, 2016) for the optimization of the solar energy intercepted for the different configurations of one and two axes devices. However, most of the works are focused on the continuous solar tracking systems and the optimization of photovoltaic panel operation, either with open or closed loop control systems. In this work results are presented for different solar tracking schemes and for different geographical conditions. The same schemes were applied to solar radiation data obtained from the new solarimetric network of México (González-Cabrera et al, 2017). These stations are maintained by the Mexican Solarimetric Service in the Institute of Geophysics at the *Universidad Nacional Autónoma de México* (UNAM), and there is part of the project Mexican Centre of Innovation in Solar Energy (CEMIESol, by its Spanish acronym). This project involves 67 academic institutions and 21 private companies, 50 individual projects with the main goals in the academic-industry linkage, the promotion of technology transfer and the technological development of capacities for companies in the solar energy area.

CEMIESol includes a specific subproject to create the National Inventory of Solar Resource in México and contemplates the creation of a national network of solarimetric reference stations. The solar radiation irradiances were measured in their principal components: global, DNI and diffuse. These data are the basis to calculate the daily irradiation over a flat plate collector at different solar tracking strategies that includes steeping tracking

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with different time intervals. This information is useful to determine the need of accuracy for a solar tracking system and determines the energy that is not collected depending on the step-time for on solar tracking.

Tab. 1: Nomenclature

Symbol	Meaning	Symbol	Meaning
H_{fc}	Global solar irradiation over flat collector	G_b	Direct normal solar irradiance
G_{fc}	Global solar irradiance over flat collector	G_D	Diffuse solar irradiance
Δt	Time interval for solar measurements	N	Number of available days for a month
H_m	Monthly mean daily irradiation	z_0	Angle of incidence over the collector
$G_{\beta b}$	Direct tilted irradiance	a_z	Solar azimuthal angle
$G_{\beta D}$	Diffuse tilted irradiance	z_e	Solar zenithal angle
$G_{\beta R}$	Reflected tilted irradiance	γ	Collector azimuthal angle
		β	Tilt angle of flat collector

2. Methodology

To numerically quantify the radiative power incident on a flat plate, a computer routine was written that allows calculating the daily irradiation in Watts-hour (Wh) according to equation 1 (eq.1). Once the daily irradiation is obtained, the monthly mean daily irradiation is calculated with the available complete days of solar radiation irradiances (N) (eq. 2).

$$H_{fc} = \sum_{day} G_{fc} \Delta t \qquad \text{(eq. 1)}$$

$$H_m = \frac{1}{N} \sum_{month} H_{fc} \qquad \text{(eq. 2)}$$

The irradiance over the flat collector is determined by equation 3, using direct, diffuse and reflected irradiance and the incidence angle over the collector. The albedo was considered the same for all stations with a value of 0.2. The total irradiance over the collector is calculated with the sum of the three mentioned components in equation 3. In equations 4, 5 and 6 are the expressions to calculate each solar component.

$$G_{fc} = G_{\beta D} + G_{\beta R} + G_{\beta b} \qquad \text{(eq. 3)}$$

Where

$$G_{\beta b} = G_b \cos(z_0) \qquad \text{(eq. 4)}$$

$$G_{\beta D} = G_D \, T_D \qquad \text{(eq. 5)}$$

$$G_{\beta R} = \rho \, [G_D + G_b \cos(z_e)] \, T_R \qquad \text{(eq. 6)}$$

The factors for diffuse (T_D) and reflected (T_R) irradiances are calculated, for simplicity in this work, with the isotropic model of Liu-Jordan (1961), and the expressions are shown in equation 7. The incidence angle (z_0) over the collector is obtained with equation 8.

$$T_R = \frac{1}{2}[1 - \cos(\beta)] \quad \text{(eq. 7)}$$

$$T_D = \frac{1}{2}[1 + \cos(\beta)]$$

$$\cos(z_0) = \cos(z_e)\cos(\beta) + [\sin(z_e)\sin(\beta)]\cos(a_z - \gamma) \quad \text{(eq. 8)}$$

The selected tracking strategies include fixed, continuous and steeped movement with different time intervals, as is described in the following bullets

Fixed

- Horizontal, the flat collector is positioned horizontally
- Fixed latitude, the flat collector is tilted by latitude facing to the South

Continuous movement

- Heliotrope, continuous movement where the normal to flat collector is pointing to the sun at any moment
- Azimuthal tracking, continuous movement with the flat collector tilted by latitude. The tracker turns with the solar azimuthal angle.

Stepped movement

- Stepped azimuthal tracking, the flat collector is tilted by latitude and the tracker turns every defined time interval in order to keep the azimuthal angle for collector in the middle of the azimuthal solar angle interval. The step-time intervals are 10, 30, 60 and 120 minutes.

The solar position is determined every minute by the Campbell Scientific® acquisition system, using the Solar Position Algorithm (Reda & Andreas, 2003) and it is reported next to the Solar radiation measurements for each station. The solarimetric data was obtained from 4 stations belonging to the Mexican Solarimetric Reference Network. The name and geographical coordinates of selected stations are reported in table 2. All stations contain the main solar parameters: global, diffuse and normal direct irradiance recorded every minute. The years selected were from 2016 to 2018.

Tab. 2: Geographical coordinates of solarimetric stations for the study

Site Name	Latitude	Longitude	Altitude MAMSL [meters]	Starting date [DD/MM/YYYY]
Mexico City	19.3260°N	99.1760 °W	2281	01/011984
Coeneo, Mich	19.8136 °N	101.6947 °W	1989	10/28/2015
Zacatecas, Zac	22.7725 °N	102.6436 °W	2317	11/17/2015
Gomez Palacio, Dgo	23.9568 °N	104.5704 °W	1877	11/19/2015

For stepped azimuthal angle from collector, was chosen to the middle of the solar azimuthal angle interval, corresponding to an interval time (fig. 1). As an example, figure 2 shows the graph for continuous azimuthal angle from the Sun compared with the stepped azimuthal angle from collector, for 60 minutes.

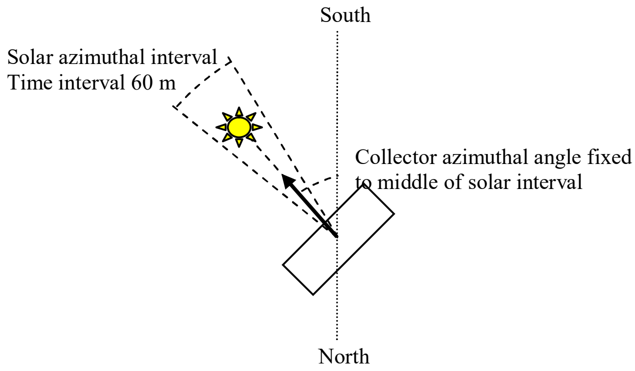

Fig. 1: Diagram of collector azimuthal angle respect the Solar azimuthal angle interval

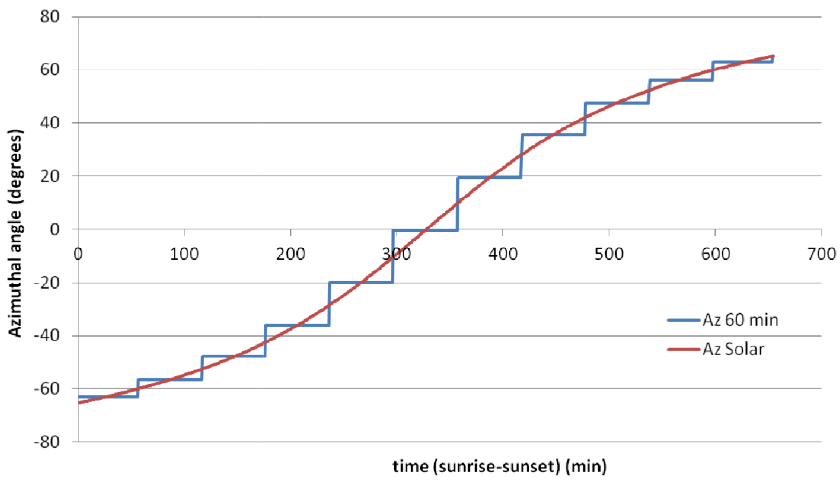

Fig. 2: Graph of continuous azimuthal angle compared with the 60 minutes stepped azimuthal angle from collector at spring equinox

3. Results

3.1. Mean monthly daily irradiation

The monthly mean daily irradiations for selected stations are shown in figure 3. This figure includes fixed and continuous tracking cases. As could be expected, cases with continuous tracking have larger amount of irradiation collected respect the fixed cases, and the heliotropes case has the best energy collection. For fixed cases the flat collector tilted with latitude have a better daily irradiation respect the Horizontal case, mainly in the autumn and winter months. This behavior is due to the solar geometry along the year, in autumn and winter months, the solar position is founded completely ant the south and the cosine factor reduces the irradiation over a horizontal collector. Otherwise, in spring and summer months the horizontal collector have a better irradiation respect the latitude tilted case, due in these months the solar position is very close to the local zenith point at noon.

Another issue, observed in figure 3, is in July and September, for Ciudad de México and Coeneo, the difference between the irradiation collected is reduced respect other months. This could be explained due this month corresponds to a rainy season, therefore the direct irradiance contribution is also reduced and the effect of the tracking is less significant.

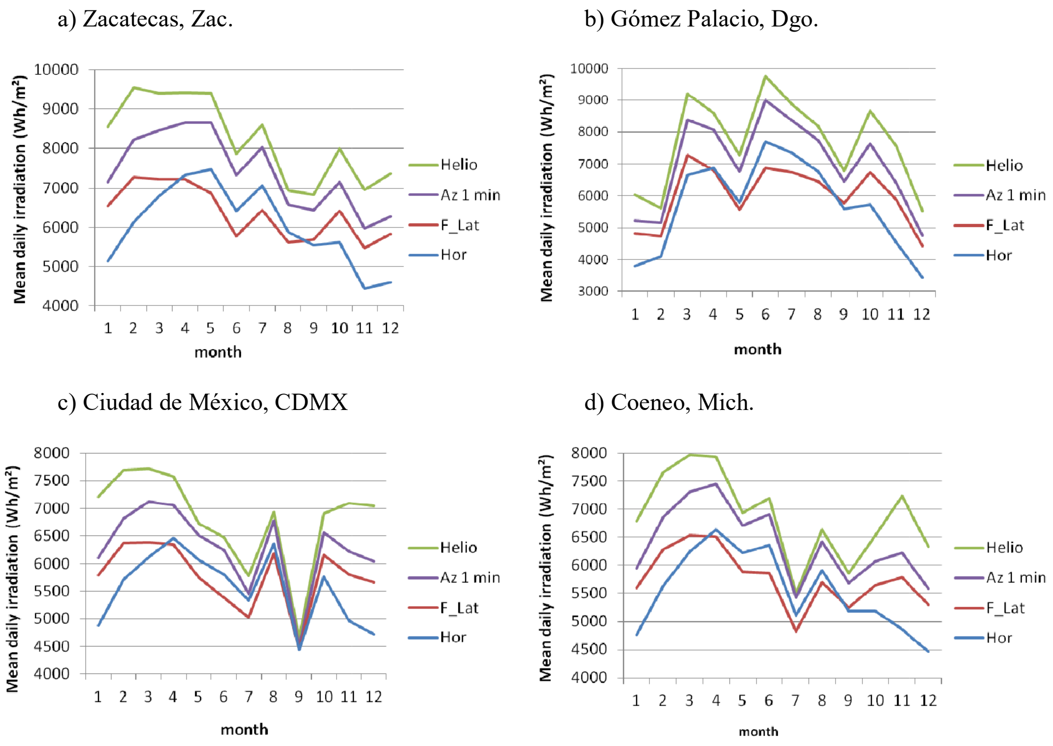

Fig. 3: Graph of monthly mean daily irradiation for fixed and continuous tracking in selected stations

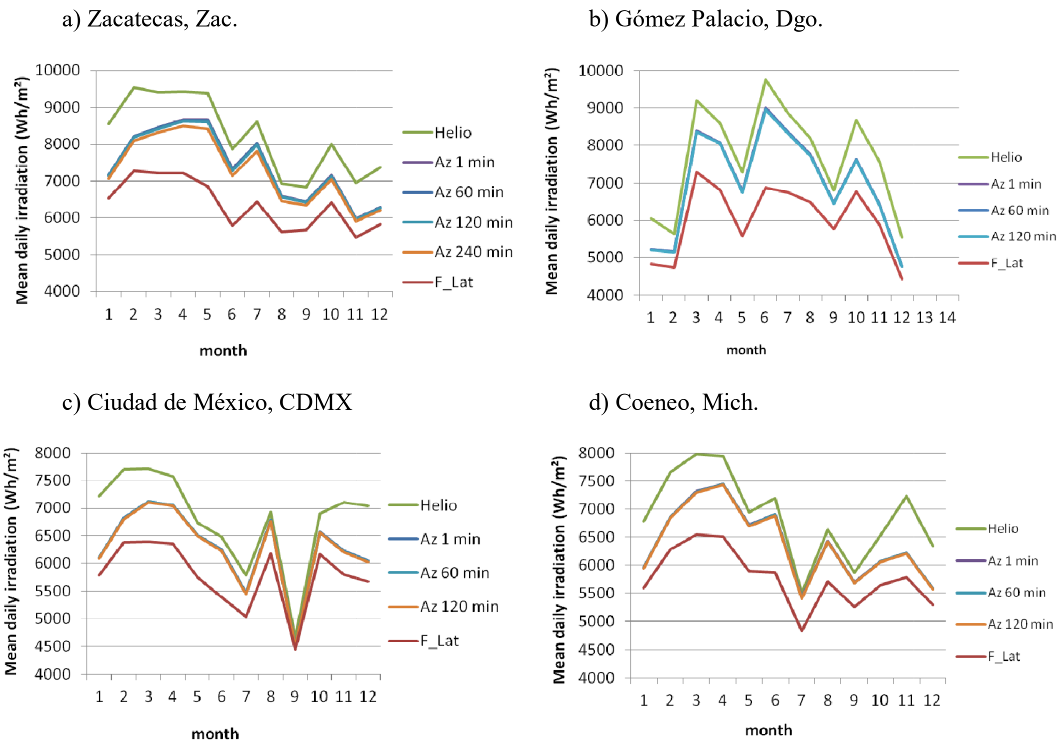

Fig. 4: Graph of monthly mean daily irradiation for azimuthal steeped tracking in selected stations

In figure 4, the steeped tracking cases are shown. As it could be expected, these cases collect less irradiation than the heliotrope case and more than the fixed collector tilted by latitude. However, it must be noted that the difference of collected irradiation is not significant for steep time intervals less than 120 minutes. The major differences respect the continuous tracking are less than 2%. The reason can be found with an analysis of angular differences.

3.2. Angular differences

It can be observed, in figure 5, the angular differences, over the collector, between the incident angles for steeped tracking, respect the continuous tracking. The differences are determined in the relation of the continuous solar azimuthal angle for the steep time intervals of 10, 60 and 120 minutes. The differences were obtained for specific days: summer and winter solstice, and spring equinox. The major angular difference corresponds to the summer solstice with values less than 15 degrees (for 120 min steep time) near to the noon. In fact, the average difference for all day is less than 1° for the case of 120 minutes steep time. This angular behavior can be observed in figure 6, for Jun-21, where the differences of azimuthal angle between steeped and continuous cases are almost not significant for most of the day.

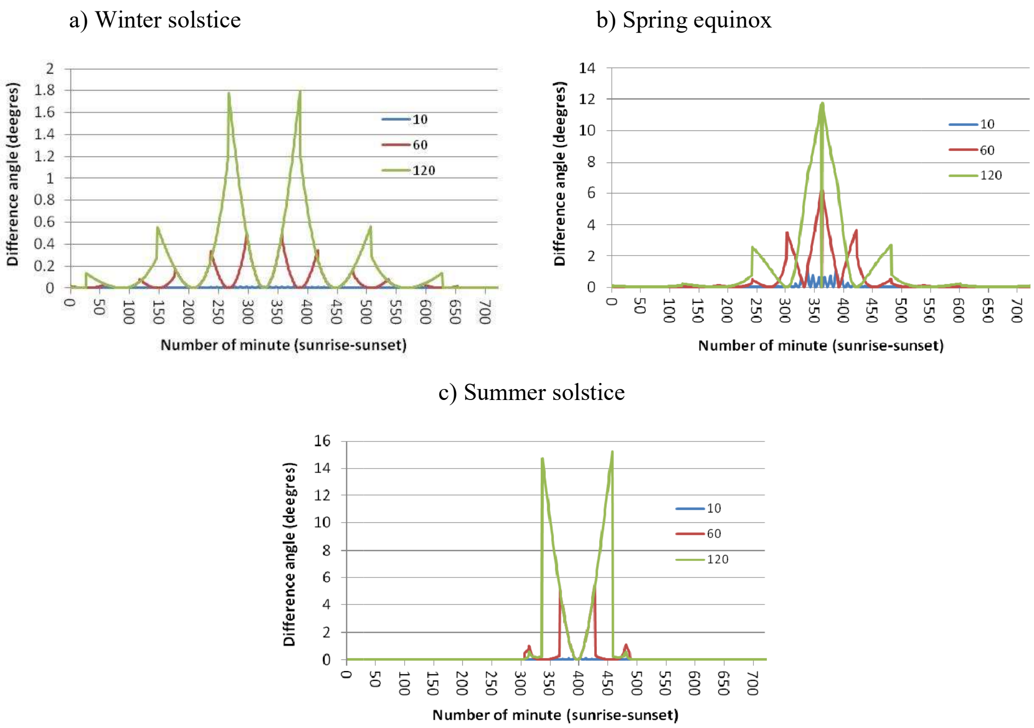

Fig. 5: Graph of continuous azimuthal angle compared with the 60 minutes stepped azimuthal angle from collector at summer solstice

If these small angular differences are taking in account with the corresponding cosine factor, the difference of calculated irradiation is even lower. For example, the percentage difference applying the cosine factor, at the summer solstice with a steep time of 120 minutes, is less than 6%, and for all day, the average difference is less than 0.5%.

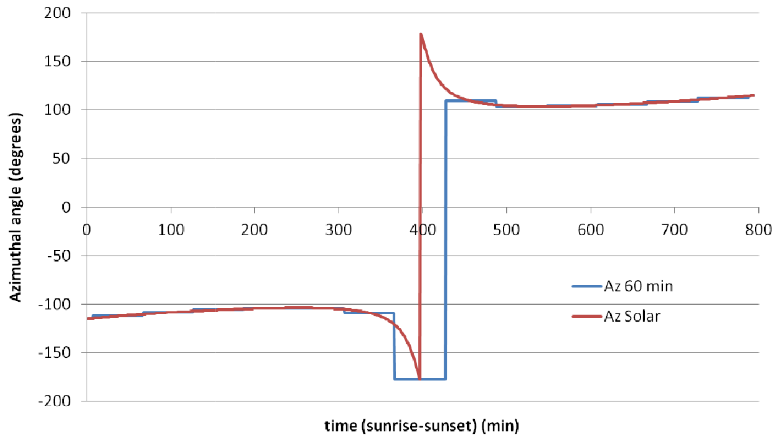

Fig. 6: Graph of continuous azimuthal angle compared with the 60 minutes stepped azimuthal angle from collector at summer solstice

Table 3 reports the annual energy captured by stepped tracking compared to that obtained by azimuthal continuous movement. All cases the difference is not significant according to the observed behavior of angular differences discussed previously. Table 4 reports the annual energy captured for the rest of cases compared with the Heliotrope tracking. It must be noted that Zacatecas have the major losses compared with the heliotrope movement due to latitude and this site have more clear days along the year. For all cases the azimuthal tracking capture near of 90% compared with Heliotrope case.

Tab. 3: Annual energy captured respect continuous tracking

Site	Azimuthal continuous	Steep 30 min	Steep 60 min	Steep 120 min	Steep 240 min
Mexico City	100%	99.99%	99.92%	99.74%	-
Zacatecas	100%	99.98%	99.91%	99.63%	99.18%
Coeneo	100%	99.99%	99.92%	99.73%	-
Gomez Palacio	100%	99.98%	99.92%	99.61%	-

Tab. 4: Annual energy captured for continuous tracking and fixed collectors respect Heliotrope Tracking

Site	Heliotrope Tracking	Azimuthal Tracking	Fixed by latitude	Fixed Horizontal
Mexico City	100%	92.20%	84.71%	81.41%
Zacatecas	100%	89.96%	77.24%	73.24%
Coeneo	100%	92.76%	83.76%	80.63%
Gomez Palacio	100%	91.20%	78.38%	74.21%

4. Conclusions

The Monthly mean daily irradiation collected by a flat collector with different tracking strategies were obtained from solarimetric data for some stations of the Mexican Solarimetric Network. The results confirm that the heliotropes cases have the best energy collection, annually azimuthal tracking loses approximately 10% of the energy and the fixed collector tilted by latitude loses between 16 to 23% of the daily irradiation. For azimuthal stepped tracking the differences respect the continuous tracking are not significant. In the worst case for a steep time of 240 minutes, in Zacatecas city, the annual loss was less than 1%.

5. References

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