Influence of terrain on single-axis PV plants

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Abstract

This paper presents a systematic study of the influence on the radiation capture of the azimuth angle of horizontal one-axis trackers as well as the inclination and azimuth of the terrain where they are built. The results prove that, to optimize the radiation capture and, consequently, the energy production, for South facing terrains, the tracker rotation axis must be also oriented to the south for any terrain inclination. Additionally, when both the terrain and the rotation axis of the trackers are oriented to the South, the radiation capture increases with the inclination of the terrain until a maximum. However, for not south facing terrains, the rotation axis azimuth of solar trackers should be deviated from the South in the same direction as the terrain azimuth. Finally, in this case of not south facing terrains, the loss of radiation increases with the azimuth of the terrain.

Keywords: Photovoltaics, Horizontal one-axis Tracking, Backtracking, Inclination of the Terrain, Azimuth of the Terrain.

1. Introduction

The environmental challenges that society is currently facing worldwide are fostering the development of renewable energies since they contribute to a more efficient and sustainable energy system (United Nations, 2019). In this context, applications based on the use of solar energy, in general, and photovoltaic (PV) energy, in particular, have an essential role to play due to the fact that the cost of energy generation associated with them has decreased significantly in recent decades thanks to technological development and research (Renewable Energy Agency, 2020; Ribó-Pérez et al., 2019).

However, the strong temporal dependence of solar energy or the negative effects that shadows produce on PV collectors make it necessary to promote new technological developments that mitigate the impact of these phenomena on energy production (Gómez-Uceda et al., 2020).

In this sense, solar tracking is presented as a solution to the strong temporal dependence of solar radiation (Hua et al., 2019). In this way, solar collectors follow the sun's path throughout the day and the year, thereby increasing solar capture and, therefore, energy production (Bahrami et al., 2016). For that reasons, multiple research on tracking is being developed to enhance the technology and its efficiency while reducing its cost (Eldin et al., 2016).

For this solar tracking, the classical tracking strategy proposes the astronomical model based on the relative Earth-Sun motion. However, several studies have shown that this is not the optimal strategy for cloudy days. The reason for this is that astronomical tracking aims to optimize the direct component of solar radiation; however, on cloudy days this component loses relevance compared to the diffuse and reflected components (Duffie & Beckman, 2013). Therefore, it is necessary to continue research on solar tracking strategies that consider the global behavior of solar radiation and not only its direct component.

On the other hand, inter shading between PV collectors reduce the radiation capture and increases the temperature of the shading PV cells that work as resistive loads and negatively influences to the functioning of the plant (Belhachat & Larbes, 2015; Satpathy & Sharma, 2019; Seyedmahmoudian et al., 2016). Multiple

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research is being developed to study the reduction in PV production due to shading (Saint-Drenan & Barbier, 2019; Satpathy & Sharma, 2019). Backtracking is a technological solution to avoid inter-shading between collectors in PV plants with tracking (Gómez-Uceda et al., 2021; Panico et al., 1992). It consists of deviating the collectors with respect to the maximum capture orientation to a new position where there is no intershading, thus mitigating the negative effects of the latter (Figure 1).

However, although both problems have been widely studied, most of the previous research has studied PV facilities located on horizontal terrains. In this context, this work presents a systematic study of the influence of the terrain characteristics (inclination and elevation) on the radiation capture of horizontal one-axis PV plants.

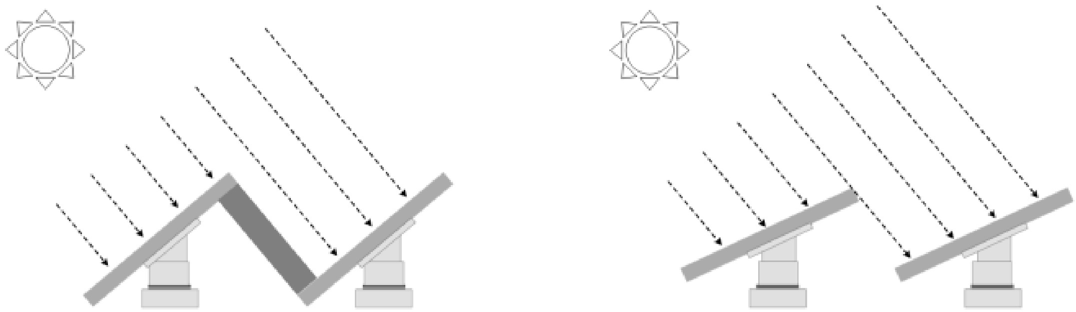


Fig.1. Fundamentals of Backtracking. Part (a) shows a situation in which one tracker shadows the next. This shadow can be avoided by decreasing the tilt of the trackers (part B)

2. Materials and Methods

For that purpose, the solar radiation reaching the collectors of a PV plant with horizontal one-axis trackers is analyzed for different terrain and collector configuration. The Hay-Davis Method (Hay, 1993) is used to estimate the solar irradiance. This method considers that the solar irradiance, I, is composed of three components: direct, diffuse, and reflected. Thus, in vectorial notation, it is given by eq. (1), where I_0 is the horizontal extraterrestrial solar irradiance, I_B and I_D are, respectively, the direct and diffuse irradiance on a horizontal surface, ρ is the albedo of that horizontal surface, and, $\vec{k}$, $\vec{n}$ and, $\vec{s}$, are, respectively, the vertical unitary vector, the normal vector to the collectors, and the solar vector, defined all of them in the terrestrial reference system.

$$I = \frac{\vec{s}\cdot\vec{n}}{\vec{s}\cdot\vec{k}} I_B + \left[\left(\frac{\vec{s}\cdot\vec{n}}{\vec{s}\cdot\vec{k}}\right)\frac{I_B}{I_{OH}} + \left(1 - \frac{I_B}{I_{OH}}\right)\frac{1+\vec{k}\cdot\vec{n}}{2}\right] I_D + \rho\,\frac{1-\vec{k}\cdot\vec{n}}{2}(I_B + I_D) \qquad \text{(eq. 1)}$$

Specifically, the solar vector, $\vec{s}$, is a unitary vector pointing the Sun and given by eq. (2) where δ is the solar declination, φ is the latitude of the location considered and $\Omega t = (2\pi/24\ rad/h)t$ is the hour angle.

$$\vec{s} = \sin\Omega t\ \cos\delta\,\vec{i} + (\cos\Omega t\cos\delta\sin\varphi - \sin\delta\cos\varphi)\vec{j} +$$
$$+ (\cos\Omega t\cos\delta\cos\varphi + \sin\delta\sin\varphi)\vec{k} \qquad \text{(eq. 2)}$$

From eq. (1) considering I as function depending of $\vec{n}$ it is possible to optimize the solar irradiance I by applying the Lagrange multiplier method. In this work, this methodology is applied to PV plants with horizontal one-axis trackers whose rotation axis has an azimuth angle γ. Furthermore, the ground on which the PV plant is built is considered not to be horizontal but to have an inclination and azimuth β and χ, respectively. Thus, the normal vector to the ground, $\vec{e}$, is given by eq. (3).

$$\vec{e} = \frac{\cos\beta\cdot\sin\gamma}{\sqrt{\sin^2\beta+\cos^2\beta\cos^2(\gamma-\chi)}}\vec{i} + \frac{\cos\beta\cdot\cos\gamma}{\sqrt{\sin^2\beta+\cos^2\beta\cos^2(\gamma-\chi)}}\vec{j} - \frac{\sin\beta\cdot\cos(\gamma-\chi)}{\sqrt{\sin^2\beta+\cos^2\beta\cos^2(\gamma-\chi)}}\vec{k} \qquad \text{(eq. 3)}$$

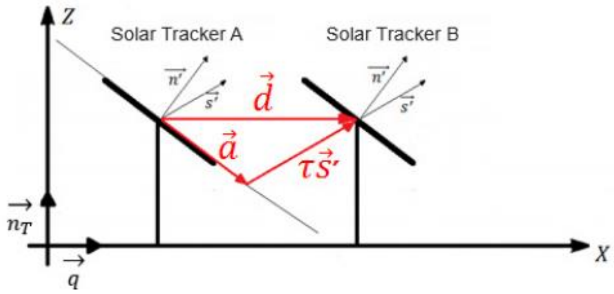


Fig.2. Geometry analysis of inter-shading between collectors.

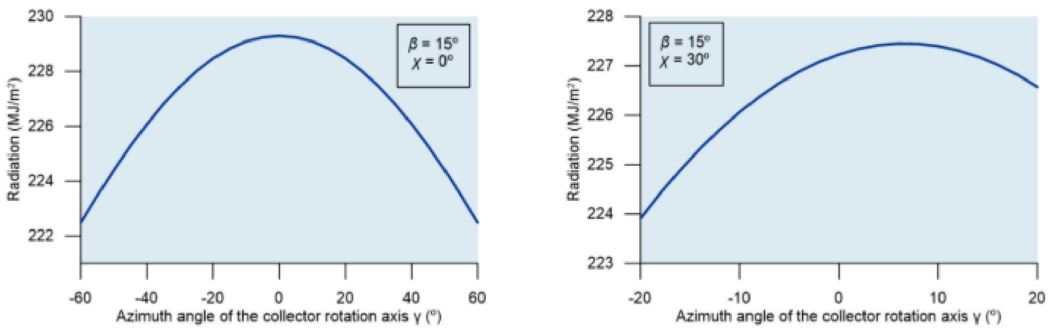
On the other hand, according to Fig. 2, inter-shading between the PV collector will take place when the module of the vector $\vec{a}$ is smaller than the width of the panels, h. As a solution, in this work, backtracking is proposed in order to avoid shading between collectors. Specifically, when inter-shading between collectors occurs, the collectors are deviated from its original position the minimum angle that avoids shading.

3. Results

The methodology described has been applied to a horizontal one-axis PV plant situated at a location of 37.75492º N latitude and -5.04548º longitude. To study the influence of the terrain on the solar irradiance capture when the trackers move according to the tracking/backtracking strategy proposed, the inclination of the terrain β has been varied from 0º to 45º (1º steps) and its azimuth χ has been varied form -60º to 60 º (5º steps). Furthermore, the azimuth of the rotation axis of the trackers γ has also been varied form -20º to 20 º (2º steps). The width of the collectors and the distance between the collector lines have remained constant, being $h = 3m$ and $d = 6m$, respectively.

It has been found that, whatever the inclination of the terrain, the maximum solar irradiance values are registered when the azimuth of the terrain is zero. Furthermore, for all terrain inclinations, when the terrain is oriented towards the south, the orientation angle of the solar trackers that optimizes solar capture must also be zero. Therefore, the most favorable situation will be when both the terrain and the axis of rotation of the trackers are oriented towards the south.

However, it has been found that when the terrain does not face south, the optimum angle for the axis of rotation of the solar trackers must also deviate from the south in the same direction as the terrain, and that this behavior is accentuated for terrain with high inclinations. As an example, Fig.3 shows the results for the case of a terrain with an inclination angle (β) of 15º. Specifically, it represents the radiation vs. the azimuth of the rotation axis of the trackers when the terrain is oriented towards the South direction, that is, $\chi = 0$, (Fig. 2a) and when $\chi = 30°$ (Fig. 2b). It can be seen that, in the first case $(\chi = 0°)$, the maximum radiation is captured when the tracker rotation axis is also orientated towards the South $(\gamma = 0°)$ whereas, in the second case $(\chi = 30°)$, it must be deviated 6º. Fig. 4 shows the most favorable orientation of the rotation axis of the trackers for different azimuth of the terrain when its inclination is 15º.



(a) (b)

Fig.3. Dependence of solar radiation on the tracker axis azimuth for: a) $\beta = 15°$ and $\chi = 0°$ and b) $\beta = 15°$ and $\chi = 30°$

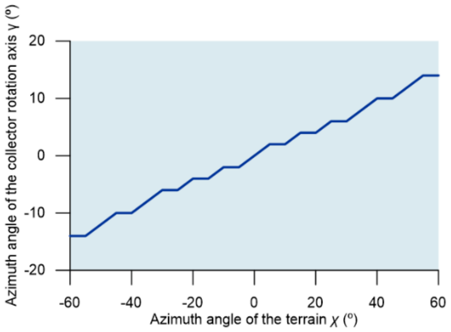
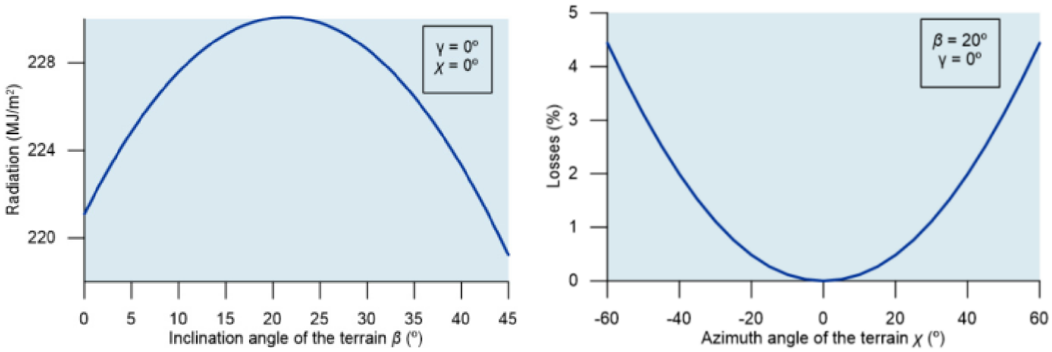


Fig.4. Optimal orientation of the rotation axis of the trackers for terrain with 15º of inclination and different azimuth χ

On the other hand, Fig. 5a shows that, when the terrain and the tracker rotation axis are oriented to the South, the radiation increases with the inclination of the terrain until a maximum value which, in the case of the location considered (37.75492º N latitude and -5.04548º longitude), occurs for $\beta = 21°$. Finally, for a fixed terrain inclination of $\beta = 20°$, Fig. 5b shows the influence of the azimuth on the radiation capture, on terms of the losses respect to the maximum irradiance that, as mentioned before, occurs when $\chi = 0°$and $\gamma = 0°$. It can be seen that these losses increase with the azimuth of the terrain.



(a) **(b)**

Fig.5. Influence on the maximum radiation capture of: a) the inclination of the terrain when $\chi = 0°$and $\gamma = 0°$ and b) the azimuth of the terrain when $\beta = 20°$and $\gamma = 0°$

4. Conclusions

This work presents a systematic study of the influence of the inclination and the azimuth of the terrain on the maximum radiation capture by the collectors of a horizontal one-axis PV plants located on that terrain whose trackers moves according to a backtracking strategy that tries to avoid inter-shading between PV collectors. Furthermore, the azimuth of the tracker rotation axis has also be considered for this study. The results show that, for any inclination of the terrain, the maximum radiation capture will take place when the terrain and the tracker rotation axis are oriented to the South. For other terrain azimuth, the higher the azimuth, the higher the losses will be. Additionally, it has been proved that the angle orientation of the rotation axis of the trackers must be deviated in the same direction as the terrain in order to maximize the solar capture. Thus, this work contributes to the characterization of one-axis PV plants and the optimization of its radiation capture, and, consequently, of its energy production.

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