Applications

Tracking and Ground Cover Ratio

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Energy yield and occupation of land are two parameters that must be optimized when designing a large PV plant. This paper presents the results of simulating the energy yield of flat panels for some locations and different tracking strategies as a function of the ground cover ratio. Some interesting results for design purposes, such as the optimal solar trackers depending on the land availability or the energy gains of every tracking strategy, are shown. For example, the energy gains associated to one north–south axis tracking, referenced to static surfaces, ranges from 18 to 25%, and from 37 to 45% for the two-axes tracker for reasonable ground cover ratios. To achieve these results, a simulation tool with appropriate models to calculate the energy yield for different solar trackers has been developed. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: PV plants; grid-connected systems; tracking; ground cover ratio

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INTRODUCTION

Solar tracking has been used with PV flat modules for more than 20 years.1 The available literature describes several cases with good performance in terms of both reliability and energy gains.2–15 Typical costs of PV grid-connected systems at current Spanish market are around 5€/Wp for static arrays (3€/Wp for PV modules plus wiring, 0.5€/Wp for support structure plus civil works, 0.5€/Wp for inverters and 1€/Wp for others) and 6€/Wp for two-axes tracking (support structure plus civil works are now 1, 5€/Wp). Then, investment increase is about 20% while energy yield increase is about 40%. This is why trackers are flourishing in this market and also why this can continue, meanwhile PV modules cost remains larger than 0.8€/Wp. We estimate that about 70% of the 106 MW installed during 2006 are combined with solar trackers. A recent market survey16 has identified up to 22 companies offering a large variety of trackers.

When many PV generators are concerned, there is an obvious relationship between land occupation and energy yield; increasing land occupation reduces mutual shading and, therefore, increases energy yield. However, this is not without a price, because land-related costs (land, wiring, fencing, civil works, etc.) also increase. Hence, the study into the relationship between land occupation and energy yield is a key point in the design of large PV plants. At the IES-UPM, we are often required to advise on practical questions about the design of PV tracking plants: What is the recommended tracker for a given terrain? What is the recommended separation between trackers? etc. In fact, answering such questions has been the main motivation for this work.

This paper deals with the relationship between land occupation and energy yield of flat panels for different tracking possibilities: two axes, single vertical axis, single horizontal axis and single tilted axis. As a matter of reference, static surfaces are also considered. Thus, tracking geometry has been reviewed and a simulation exercise for different places has been carried out.
**TRACKING GEOMETRY**

The receiver position and the incident angle are relevant parameters as far as tracking is concerned. Tracking geometry descriptions can be found in the available literature for many years. Those based on matrix\textsuperscript{17} are particularly consistent but not very intuitive and rather cumbersome when implemented in software codes. That is why some authors have developed equations directly relating position and incident angles with a particular motion. However, they were given with specific constraints. For example, the classic book by Duffie and Beckman\textsuperscript{18} provides useful equations but only for surfaces that rotate on axes parallel to the surfaces. Hence, despite these antecedents, there is a need to develop a set of equations for arbitrarily oriented surfaces, also able to take shading into account, and still easy to implement in software codes.

Figure 1 describes the solar coordinates referred to a system whose X, Y and Z axis are pointing, respectively, to West, South and Zenith. It is not difficult to deduce these coordinates in relation to solar elevation, $\gamma_s$, and solar azimuth, $\psi_s$, angles by

\[
x = \cos \gamma_s \sin \psi_s; \quad y = \cos \gamma_s \cos \psi_s; \quad z = \sin \gamma_s
\]

At any given moment, the solar elevation and azimuth angles are calculated from the equations

\[
\sin \gamma_S = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega \quad (2)
\]

and

\[
\cos \psi_S = (\sin \gamma_s \sin \phi - \sin \delta) / (\cos \gamma_s \cos \phi) \quad (3)
\]

where $\delta$, $\phi$ and $\omega$ are, respectively, the latitude, the declination and the hour angles.

**Single vertical axis**

For a plane with a fixed slope, $\beta_{\text{GEN}}$, rotated around a vertical axis, the angle of incidence is minimized when the surface azimuth and solar azimuth angles are equal. Axis rotating angle, $\omega_{\text{ID}}$ (‘ID’ means ideal value) and incidence angle, $\theta_S$, are easily determined from Figure 2.

\[
\omega_{\text{ID}} = \psi_s \quad (4)
\]

\[
\theta_S = \gamma_S - \beta_{\text{GEN}} \quad (5)
\]

**Single horizontal axis**

For a plane rotated around a horizontal axis and forming a fixed angle with this axis, $\beta_{\text{GEN}}$, the angle of incidence is minimized when the axis, the line to the Sun and the normal to the surface are on the same plane. Relevant equations are determined from Figure 3.

\[
\tan \omega_{\text{ID}} = \frac{x}{z} = \frac{\cos \gamma_s \sin \psi_s}{\sin \gamma_S} \quad (6)
\]

\[
\theta_S = \arctan \left[ \frac{y}{(x^2 + z^2)^{1/2}} \right] - \beta_{\text{GEN}} \quad (7)
\]

**Single tilted axis**

For a plane rotated around a single axis oriented to the south and tilted an angle, $\beta_{\text{AXIS}}$, and forming a fixed angle with this axis, $\beta_{\text{GEN}}$, the angle of incidence is minimized, again, when the axis, the line to the Sun and the normal to the surface are on the same plane. In

![Diagram of sun coordinates referring to the site](image)

Figure 1. Sun coordinates referring to the site

![Diagram of vertical tracking](image)

Figure 2. Vertical tracking: (a) plane of the line to the Sun and the normal to the surface. (b) View of this plane showing incidence angle
order to deduce the relevant expressions, it is best to refer the position of the Sun to the OX0Y0Z0 system resulting from turning the previous OXYZ system just an angle \(b_{AXIS}\) around the X axis, as shown in Figure 4. Then, the Sun coordinates at the new system are given by

\[
\begin{align*}
x' &= x; \\
y' &= \rho \cos(\theta + \beta_{AXIS}); \\
z' &= \rho \sin(\theta + \beta_{AXIS})
\end{align*}
\] (8)

where

\[
\rho = (y^2 + z^2)^{1/2} \quad y = \arctan(z/y)
\] (9)

Now, relevant expressions can be deduced through a simple analogy with the previous case. Thus,

\[
\omega_{ID} = \arctan\left(\frac{x'}{z'}\right)
\] (10)

\[
\theta_{S} = \arctan\left[\frac{y'}{(x'^2 + z'^2)^{1/2}}\right] - \beta_{AXIS}
\] (11)

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure4.png}
\caption{Meridian view of YZ and Y'Z'axis}
\end{figure}

### Two axes

Two-axes tracking is obtained when adding the capability to rotate the receiving plane around a second axis normal to the first one to a single axis tracking. Then, this plane can always be kept normal to the sun. The new angle, \(\beta_{GEN-TRAC}\), depends on the first type of axis. When this is vertical (see Figure 2b)

\[
\beta_{GEN-TRAC} = \gamma_{S}
\] (12)

Similarly, Figure 3b leads to determining when the first axis is horizontal

\[
\beta_{GEN-TRAC} = \arctan\left[\frac{y}{(x^2 + z^2)^{1/2}}\right]
\] (13)

and when it is tilted

\[
\beta_{GEN-TRAC} = \arctan\left[\frac{y'}{(x'^2 + z'^2)^{1/2}}\right]
\] (14)

### Shading

PV generators often include several trackers. Depending on the Sun’s position, partial shading between two adjacent trackers may occur, mainly in the early morning and late evening.

#### Single horizontal axis

Figure 5 shows the projection at the XZ plane of two adjacent trackers, at a distance \(L_{EW}\) (distance at the EW direction), when shading occurs. Horizontal shadow length, \(s_{EW}\), and shaded fraction, \(F_{S_{EW}}\), are given by

\[
s_{EW} = \frac{1}{\cos \omega_{ID}} \quad \text{and} \quad F_{S_{EW}} = \max\left[0, 1 - \frac{L_{EW}}{s_{EW}}\right]
\] (15)

#### Single tilted axis

Figure 6 shows a projection at the plane of the Y axis and normal to the surface when shade in the NS direction takes place. This figure applies to receptors rotated around a horizontal axis and forming a fixed angle, \(\beta_{GEN}\), with this axis, and also for receptors rotated around a tilted axis, \(\beta_{AXIS}\), and coplanar with
this axis. In other words, this figure applies when only a
tilt angle, $b_{\text{GEN}}$ or $b_{\text{AXIS}}$, differs from zero. Tracker
length and distance, both in the NS direction, are
respectively $b$ and $L_{\text{NS}}$. Then, horizontal shade length,
$s_{\text{NS}}$, and shaded fraction, $F_{S_{\text{NS}}}$, are given by

$$s_{\text{NS}} = b \left( \cos \beta + \frac{\sin \beta}{\tan B} \right)$$  (20)

$$\tan B = \left( \frac{x^2 + z^2}{y} \right)^{1/2}$$  (21)

$$F_{S_{\text{NS}}} = \max \left[ 0, \left( 1 - \frac{b \cdot L_{\text{NS}}}{s_{\text{NS}}} \right) \right]$$  (22)

In these equations $\beta$ can represent, both, $b_{\text{GEN}}$ or $b_{\text{AXIS}}$.

It can be observed that the following value of $L_{\text{NS}}$

$$L_{\text{NS}} = b (\cos \beta + \sin \beta \cdot \tan (\phi + \delta_M))$$  (23)

just avoids shade at noon for all the days throughout the
year, where $\delta_M$ is the maximum declination angle
throughout the year ($\delta_M = 23.5^\circ$).

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throughout the year ($\delta_M = 23.5^\circ$).
two different conditions: First, the shade borderline must reach the front of the rear trackers and, second, shade must impinge on a tracker and not only on the empty space between two trackers. However, a reasonable approximation, in particular for relatively low $L_{EW}$ values (let us say, $L_{EW} < 3$) consists of only considering the first condition. Then,

$$FS_{NS} = \max \left\{ 0, \left( 1 - \frac{s'}{s_{NS}} \right) \right\} \quad (34)$$

where

$$s' = \frac{L_{NS} - \sin \psi_{S}}{\sin (\pi/2 - \psi_{S})} \quad (35)$$

Two axes

Shade considerations already taken into account for vertical axis trackers can also be applied for two axes trackers, when considering that the tilt angle is now the complementary to the Sun’s elevation angle.

ENERGY YIELD CALCULATION

There are a number of software tools available to simulate the energy yield of PV grid-connected systems.\textsuperscript{19–23} However, none of them can deal with all of the possible tracking strategies. Hence, we have developed our own code, comprising the following steps:

1. Obtaining solar radiation site information (the 12 monthly averages of the daily horizontal global irradiation, the daily maximum ambient temperature and the daily minimum ambient temperature) from available databases.
2. Preparation of horizontal (both global and diffuse component) irradiance sequences (it can be selected hourly or minute time intervals).
3. Determination of the position of the Sun and the receiving surface, and the incidence angle.
4. Determination of shade.
5. Transposition from horizontal to inclined irradiance values.
6. Calculation of the losses of dirty PV modules.
Table I. Models used to simulate the energy yield of a grid-connected PV plant

<table>
<thead>
<tr>
<th>Step</th>
<th>Comment/Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Solar irradiation site information</td>
</tr>
<tr>
<td>2</td>
<td>Irradiation to irradiance (horizontal)</td>
</tr>
<tr>
<td>3</td>
<td>and 4 Geometry</td>
</tr>
<tr>
<td>5</td>
<td>In-plane irradiance</td>
</tr>
<tr>
<td>6</td>
<td>Degree of cleanliness and incidence angle effects</td>
</tr>
<tr>
<td>7</td>
<td>Shading effects</td>
</tr>
<tr>
<td>8</td>
<td>PV array output power</td>
</tr>
<tr>
<td>9</td>
<td>Inverter output power</td>
</tr>
<tr>
<td>10</td>
<td>Transformer efficiency versus output power</td>
</tr>
</tbody>
</table>

7. Calculation of the losses of PV modules in the shade.
8. Calculation of the PV array output power.
9. Calculation of the inverter output power.
10. Calculation of the low voltage/medium voltage transformer output power.

Table I sets out brief explanations for each step. It is worth mentioning that soiling impact can be very significant when dry climates are concerned, as it is the case in most of Spain. Our code paid particular attention to this fact, supported by Reference 29 at step 6. This not only allows soiling impact on PV modules to be into consideration but also soiling impact in angular reflection losses.

**SELECTED CASES**

Although there are a large variety of trackers, the tracking strategies considered in this paper are the most extended ones on the current market: two axes, one vertical axis, one north–south horizontal axis and one north–south horizontal axis tilted 20°. We have also considered, as a reference, the case of a static surface with an optimal tilt, that is the tilt that maximizes the annual incident irradiation.

The output power of a PV array can be described by

\[
P = P^* \frac{G}{G^*} \left(1 - \beta(T_c - T_c^*)\right)
\]  

(36)

where \(T_c = T_a + KG, P^*\) is the nominal power of PV generator, \(G^* = 1000\text{W/m}^2\), \(G\) is the irradiance on the PV generator’s surface, \(K\) and \(\beta\) are characteristic parameters of the solar cell technology, and \(T_a\) is the ambient temperature. The good behaviour of this rather simple approximation to the power output of PV modules has been validated by recent studies.\(^ {31}\)

Here we assume that shading affects the direct and circumsolar components of the incident irradiance, and not the isotropic components. Hence,

\[
G_{BS} = B + D^{iso} + D^{circumsolar} + R
\]

\[
G_{AS} = (B + D^{circumsolar}) \left(1 - FS\right) + D^{iso} + R
\]

where \(G_{BS}\) and \(G_{AS}\) represent the irradiance before and after shading consideration respectively, and \(B, D\) and \(R\) respectively, are the direct, diffuse and reflected components of the irradiance.
For a given shaded fraction $FS$, defined as the ratio between the shaded area and the total area of a PV generator surface, the power reduction $SI$, depends on the particular electric PV system layout (mainly solar cells series and parallel association, bypass-diode disposition and inverter arrangement). Whatever be the case, it encompasses two extremes:

(a) The most optimistic is when the power reduction is just equal to shaded fraction ($SI = FS$).
(b) The most pessimistic is when the mere existence of any shade fully avoids power ($FS > 0 \rightarrow SI = 1$).

This paper analyses these two extremes and the case detailed in Figure 10, which can be often found in real PV plants: the PV generator carried by a tracker is made by the parallel association of three rows, each made up of the series association of a certain number of PV modules. Thus, each time one row gets shaded output, power reduces by one third. ($0 < FS < 1/3 \rightarrow SI = 1/3$; $1/3 \leq FS < 2/3 \rightarrow SI = 2/3$; $2/3 \leq FS \leq 1 \rightarrow SI = 1$).

Land occupation is established by the so called Ground Cover Ratio, GCR, defined as the ratio between PV array area to total ground area. For simplicity, we have restricted our analysis to the following cases:

- single vertical axis (with $\beta$ = location latitude) and two-axes individual trackers are all square ($b = 1$)
- single pure horizontal axis is understood as infinitely large ($GCR = 1/L_{EW}$)
- single tilted axis is three times longer than wide ($b = 3$) and $L_{NS}$ is selected to avoid shading in this direction fully, which is close and avoids shading at the noon winter solstice. It can be shown that this condition leads to $L_{NS} = b(\cos \beta + \sin \beta \cdot \tan(\delta_M))$, where $\Phi$ is the location latitude and $\delta_M$ the maximum value of the declination angle ($\delta_M = 23.5^\circ$) ($GCR = b/(L_{NS} \cdot L_{EW})$).

Figure 10. Electrical layout of a PV generator considered here

Figure 11. Evolution of yearly energy yield in Almería for the tracking strategies considered here, for the optimistic shading case and assuming a constant dirtiness degree of 3%
Finally, it must be noted that when shading occurs, it is possible to avoid it by moving the surface angles away from their ideal values, just enough to get the shadow borderline to pass over the border of the adjacent tracker. This is called ‘back-tracking’, and is in fact implemented in some commercial products. However, ‘back-tracking’ will be dealt with in a future paper.

**RESULTS**

As a representative example, Figure 11 shows the evolution of the yearly energy yield for the tracking strategies considered here, as calculated for Almería, for the optimistic case and assuming a constant degree of dirtiness of 3% (Normal transmittance = 0.97). Table II details the numerical results for some GCR values, referring to the case of an optimally tilted static surface. Outstanding facts are:

- There is like a ‘surrounding curve’ describing the relationship between maximum energy yield and GCR.
- This contour curve roughly, coincides with horizontal tracking for $1 < 1/GCR < 2$, with a north–south tracking axis tilted $20^\circ$ for $2 < 1/GCR < 4$ and with two-axes tracking for $1/GCR > 4$.

![Figure 12. Evolution of yearly energy yield in Almería for the tracking strategies considered here, for the realistic shading case and assuming a constant dirtiness degree of 3%](image-url)
– When comparing them with static surfaces (1/GCR = 2), energy gains associated to practical trackers range from 18–25% (horizontal axis, 1/GCR = 2–4) to 37–45% (two axes, 1/GCR = 5–10).
– Single vertical axis provides 96% of the energy provided by two-axes tracking (1/GCR = 5).
– Tilting the PV modules over the horizontal axis leads to very similar results as tilting the axis over the horizontal.
– North–south axis tilted 20° and single vertical axis show very similar results when 1/GCR → ∞.
– North–south axis tilted 20° provides the same energy yield as two-axes tracking when 1/GCR = 4, 4, and it represents 90% of the maximum energy yield of a practical tracker (two-axes with 1/GCR = 10).

Figures 12 and Table III, and Figure 13 and Table IV detail the results of a similar exercise but for the previously called realistic and pessimistic cases, respectively. In order to make the reader’s task easier, Figure 14 puts together the three cases corresponding to two-axes tracking. It can be seen that the same comments for the optimistic case apply here with some additional remarks:
– The contour curve is made up of the same tracking strategies, but the more pessimistic the shading case,
the wider the portion of the contour occupied by the north–south tracking axis tilted 20°.

- Energy gains referenced to static surfaces (1/GCR = 2) decrease, ranging from 11% (horizontal axis, 1/GCR = 2) to 40% (two axes, 1/GCR = 10) for the realistic case, and from −5 to 35% for the pessimistic case.

- When comparing with the optimistic shading case (1/GCR = 5) for the two-axes tracking, the energy yield of the realistic case is the 92% and the pessimistic case is the 85%.

Finally, Table V sets out the results of extending the simulation exercise for the realistic case to several Mediterranean places. It can be noted that, despite relatively large variations in latitude and clearness index, the previous comments essentially remain the same. It is worth to note that these results can be different than the ones given by other available tools. It is not easy to determine the causes of these differences due to the details of the internal models of these tools are out of the knowledge of the authors of this paper. For example, the impact of shadows in the output power of PV modules is highly dependant of the shading case, as it has been shown. The model to characterize the degree of cleanliness of PV modules and the incidence angle effects can also explain some of these differences.

<table>
<thead>
<tr>
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<th>Estático</th>
<th>N–S</th>
<th>N–S (0° 20°)</th>
<th>N–S (20° 0°)</th>
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Figure 14. Comparison of yearly energy yield in Almería for the two-axes tracking, for the shading cases considered here.
CONCLUSIONS

A comprehensive set of equations describing the Sun’s tracking geometry and a complete procedure to calculate the energy yield of a flat PV module grid-connected system have been presented. Based on these, the relationship between the yearly energy gains and land occupation has been analysed for several tracking strategies. The outstanding results are as follows:

- There is a ‘surrounding curve’ describing the relationship between maximum energy yield and GCR, made up of three different tracking strategies; horizontal tracking for $1 < 1/GCR < 2$, north-south axis tilted $20^\circ$ tracking for $2 < 1/GCR < 4$ and two-axes tracking for $1/GCR > 4$. When more pessimistic shading models are used, the contour curve remains but the portion of the contour occupied by the north-south axis tilted $20^\circ$ tracking is wider.

- The energy gains associated to practical trackers referenced to static surfaces ($1/GCR = 2$) has been calculated. For the optimistic shading case, these gains range from 18–25% (horizontal axis, $1/GCR = 2$–$4$) to 37–45% (two axes, $1/GCR = 5$–$10$).

- Tilting the PV modules over the horizontal axis leads to very similar results as tilting the axis over the horizontal.

- The influence of the shading model is more important when the land occupation in larger. As a practical example ($1/GCR = 5$), and taking the optimistic shading case as a reference for the two-axes tracking, the energy yield of the realistic case is 92% and the pessimistic case is 85%.

The extension of this simulation exercise to several European places has shown that despite the relatively large variations in latitude and clearness index, the previous results are applicable.

REFERENCES


Table V. Yearly energy yield for the tracking strategies considered here and the realistic shading case for some GCR values and referenced to the case of an optimally tilted static surface. Comparison of some Mediterranean locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Lat (°)</th>
<th>Kt</th>
<th>N–S</th>
<th>N–S (0° 20°)</th>
<th>Azimuthal</th>
<th>Two-axes</th>
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<tr>
<td>I/GCR</td>
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<td>Sevilla</td>
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<td>1.25</td>
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<tr>
<td>Toledo</td>
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<td>0.571</td>
<td>1.11</td>
<td>1.25</td>
<td>1.28</td>
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<tr>
<td>Tel-Aviv</td>
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<td>1.16</td>
<td>1.28</td>
<td>1.31</td>
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<tr>
<td>Crete</td>
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<td>0.546</td>
<td>1.15</td>
<td>1.28</td>
<td>1.30</td>
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<tr>
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<tr>
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<td>1.22</td>
<td>1.24</td>
<td>0.94</td>
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</tbody>
</table>


19. PV Design Pro, Maui Solar Energy Software Corporation, Haiku, USA.


25. Available at http://eosweb.larc.nasa.gov/sse


