An approach to evaluate the energy advantage of two axes solar tracking systems in Spain

Fernando Cruz-Peragón a, Pedro J. Casanova-Peláez b, Francisco A. Díaz a, Rafael López-García a, José M. Palomar a,*

a Dep. of Mechanical and Mining Engineering, Escuela Politécnica Superior de Jaén, University of Jaén, Campus Las Lagunillas s/n, 23071 Jaén, Spain
b Dep. of Electronic Engineering and Automatics, Escuela Politécnica Superior de Jaén, University of Jaén, Campus Las Lagunillas s/n, 23071 Jaén, Spain

A R T I C L E   I N F O
Article history:
Received 21 January 2011
Received in revised form 8 July 2011
Accepted 11 July 2011
Available online 20 August 2011

Keywords:
Solar tracking
Photovoltaic solar system
Profitability
Spain

A B S T R A C T
The present work shows an alternative method for determining the tracking energy advantage, defined as the additional electrical energy produced by two axes tracking systems respect to fixed devices, in order to analyze the economical profitability in Spain. For this purpose, 52 main cities of this country have been analyzed. The proposed methodology starts from irradiation data, combining diffuse models and daily–hourly relations. Different types of losses have been evaluated, and the electrical behavior of the systems has been incorporated. Final annual energetic results demonstrate that two axes devices show a relevant energy advantage (higher than 20%) for most of the national territory.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

During the last few years, photovoltaic solar systems have become one of the most popular renewable energy sources in Spain. 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 [1–3], especially in Spain [4,5]. Previous analyses demonstrate that considerable gain in the generated electricity can be reached using this technology, in particular for two axes systems [6–11]. However, it is required to evaluate if additional economic costs still guarantee the profitability of these systems.

The best way to evaluate solar systems is to use information of solar irradiance, measured throughout the time. Nevertheless, this is only possible after a systematic and rigorous instantaneous measurement of the radiation at the location of study. In practice, the big quantity of data makes its use impracticable, making it necessary to reduce the information volume. For this purpose, pyranometers or satellite images are commonly used to catch the global irradiance on a horizontal surface (in the same way, it is possible to measure the direct and diffuse components over horizontal surface in a certain place). Most available information of different places in earth (for example, main Spanish cities), corresponds to monthly average daily radiation on horizontal surface \( H_{DG} \) (kJ/m²).

This information has been obtained by integrating measurements of global irradiance distribution over horizontal surface \( I_{DG} \) (kW/m²). In this sense, there exists different global irradiation databases available, such as METEONORM [12], European Atlas of solar irradiation [13], PVGIS (http://re.jrc.ec.europa.eu/pvgis/) [14], or CENSOLAR [15]. However, some mismatches between different sources are observed [16].

On the other hand, one major advantage of flat plate solar systems (both thermal and photovoltaic) is the use of both components of the solar radiation (beam and diffuse). These components can be estimated from irradiance data and corresponding models [17].

The purpose of the current work is to quantify the additional solar gain of tracking system respect to fixed devices to demonstrate their economical viability in Spain. For this reason different issues have been considered, such us irradiation data and models providing instantaneous irradiances over horizontal, tilted and tracking surfaces, motion limits, shadows influence and efficiency of the generation system (cells, inverters, etc.). Instantaneous results have been integrated over the year, obtaining annual results. Different issues have been evaluated for one location (Jaén) over a year for instantaneous data, validating the proposed procedure for this location. In addition, some associated parameters have been estimated to adopt a simplified methodology in all the territory. Thus, the analysis has been extended to most of the cities in Spain, and a practical range of gains along this national territory has been obtained.
2. Materials and methods

2.1.1- Experimental devices for measuring instantaneous data and models

To evaluate the robustness of the proposed method, some tasks have been carried out at a location corresponding to the city of Jaén (latitude: 37.5°N; longitude: 3.47°W; altitude: 570 m.). Data of irradiance over horizontal surface for this location have been collected and published by the investigation group MatRas (http://www.ujan.es/dep/fisica/estation3.htm) [18]. They employed a Kipp & Zonen CMP11 pyranometer placed over the roof of a building.

Several instantaneous diffuse models have been evaluated (that will be discussed later) in order to predict the irradiances over both tilted and tracking surfaces, using instantaneous irradiance measurements over horizontal surface.

To valuate the final results and establish the efficiency losses for the whole generation system, electrical generation data for a little tracking system has been used. This device incorporates a little amorphous photovoltaic cell, storing data along a year. The system takes into consideration the knowledge associated to mechanical, electrical and control tasks, such as other devices [19,20]. Although there are experiences to align the device with sensors [21], here the alignment has been done following the sun polar coordinates at each time.

2.2. General procedure

Monthly average daily radiation over horizontal surface \( H_0 \) data [15] have been used as a starting point for this analysis. From these data, global irradiation over tilted surface can be obtained using certain diffuse models and associated relations:

(a) One of the most widely known and used isotropic model in this work is the Liu and Jordan model [22], which assumes an uniform distribution of the diffuse radiation on the celestial hemisphere. This model underestimates the value of the diffuse radiation in clear skies, while it works very well for covered days. In any case, the whole estimated irradiation is below the real value within a 3% [23,24].

(b) On the other hand, anisotropic models consider a bigger diffuse component in the circumsolar zone that comes directly from the direction of the solar beams. [25–30]. From the analysis of different methodologies, it has been observed that the Reindl anisotropic model [26] is quite useful in latitudes similar to those into the Spanish territory [24].

In any case, the use of both diffuse models makes it possible to establish the upper and lower limits in which results can be reliable. They will define the most favorable scenario (with maximum annual radiation values) and the most unfavorable one (with minimum annual radiation values).

Fig. 1 summarizes the general adopted methodology.

The first step (see Fig. 1) consists of determining both the maximum annual solar exposure \( F_S \) (kWh m\(^{-2}\) year\(^{-1}\)) and their corresponding surface tilt \( \theta_{op} \), using both isotropic and anisotropic diffuse models. The long-term established procedure that appears in the literature for determining the incoming solar energy in a tilted surface has been carried out [26,31–33]. Different inclinations have been also considered (with surface azimuth angle \( \gamma_{op} \) equal to zero, that is, oriented to the south), and the corresponding annual irradiation have been evaluated. The maximum value determines the optimum surface slope \( \theta_{op} \) at each place for the considered diffuse model. Subsequently, an average generation efficiency for fixed system \( \eta_{af} \) is applied to \( F_S \) in order to obtain the energetic response of the system \( F \) (kWh m\(^{-2}\) year\(^{-1}\)). This value constitutes the reference datum to evaluate the tracking improvements.

On the other hand, the yearly tracking response \( J \) (kWh m\(^{-2}\) year\(^{-1}\)) is analyzed for the tracking device. It is obtained by integrating instantaneous daily results. The ratio between \( J \) and \( F \) constitutes the fractional gain in the energy production of a tracking system in relation to an optimum fixed one. In a percentage basis, the tracking advantage \( \Delta J(\%) \) is defined as follows:

\[
\Delta J(\%) = 100 \cdot \left( 1 - \frac{J}{F} \right) \quad (1.a)
\]

Additionally, a maximum tracking advantage \( \Delta J_0 \) can be defined in a similar way to Eq. (1.a) if no restrictions in the yearly response of the system are considered \( J_0 \) (kWh/year). It will be discussed next.

\[
\Delta J_0(\%) = 100 \cdot \left( 1 - \frac{J_0}{F} \right) \quad (1.b)
\]

2.3. Tracking analysis

Fig. 2 summarizes de procedure for the daily instantaneous evaluation of a tracking system. All the parameters have been distributed into different vectors (with length \( N \)). In order to establish data along the day of study, all of them have been related to a time vector \( T \) corresponding to time steps of 1 min.

Initially, the global irradiance \( G_{in} \) (kW/m\(^2\)) and their components (beam \( GB \), diffuse \( GD \) and reflected \( GR \)) over the surface of a tracking system surface are evaluated considering that the angle of incidence \( \theta \) of the beam component is always equal to \( 0^\circ \) during the solar time (that is, assuring maximum beam irradiance).

For this purpose, the hourly–daily relations have been considered [34] by determining the hourly irradiation \( H_j \) (kJ m\(^{-2}\) day\(^{-1}\)) from daily solar exposures over horizontal surface \( H_0 \) (kJ m\(^{-2}\) day\(^{-1}\)), for each hour \( j \), such as Eq. (2) shows:

\[
H_j = r_j^h H_0; \quad r_j^h = \pi \left( a + b \cos \omega_j \right) \frac{\cos \omega_j - \cos \omega_0}{\sin \omega_0 - \cos \omega_0 \cos \omega_j}
\]

\[a = 0.409 + 0.5016 \sin (\omega_0 - \pi/3);\]

\[b = 0.6609 - 0.4767 \sin (\omega_0 - \pi/3)\]

In this equation, \( \omega_j \) corresponds to the sun hour angle and the sunset hour angle is denoted by \( \omega_0 \). The same expression has also been used to determine an instantaneous distribution of the global irradiance along the day on a horizontal surface \( L_c \) (kW/m\(^2\)). Results inferred by integrating the obtained curve agree with \( H_0 \).

Subsequently, Erbs et al. correlation [35] makes it possible to find the diffuse component of irradiation \( I_D \), using the clearness index \( k_t \) at each time. The beam component \( I_B \) is then obtained from the difference between \( I_c \) and \( I_D \):
Fig. 1. General analysis procedure developed for a particular location.

Fig. 2. General procedure of instantaneous evaluation of solar irradiation over a tracking surface.
The system must be blocked and 1 if it is moving. The distribution of values equal to 1 into this vector depends on the time intervals in which the system must be blocked.

2.3.2. Time steps motion

An ideal solar tracking process consists on following the solar motion instantaneously along the time. Nevertheless, mechanical configurations, control devices and actuators make the system moving by steps, with no motion time periods. In this case, it is necessary to determine the energy losses for different time steps according to the daily sun path. In this sense, a time stop vector \( T_{STOP} \) has been included into the analysis. It contains only zeros and ones values. The values \( j \) into this vector will be equal to 0 when the system must stay blocked and 1 if it is moving. The distribution of values equal to 1 into this vector depends on the time intervals in which the system must be blocked.

2.3.3. Shadow losses

The geometric configuration of the solar field implies that some plates over one individual tracker receive shadows from others at each moment. Thus, annual integrated global losses between 2% and 6% appear [37]. Geometric considerations must be considered in the instantaneous analysis (described in Fig. 3), in order to establish an initial evaluation of shadow losses [38–40]. The highest influence in partial shadowing is always produced by the nearest 3 sets [37], such as Fig. 4 shows. Distances \( X, Y \) and \( Z \), and surface width \( L \) and height \( H \) will be the main geometric characteristics associated to this study. A simplified method to analyze the shadow problem is to evaluate a typical squared distribution \( X = Y \), in horizontal position \( Z = 0 \) and observe what happens throughout the solar day, modifying separation distances between trackers, considering unitary height \( H = 1 \) [41].

It must be considered that shades only affects the reception of the beam constituent of radiation in the related surface. Nevertheless, the diffuse part is always captured from the sky, although in a less quantity. In relation to the reflected constituent, this can be considered as negligible, due to the obstacles surrounding the system in study.

2.3.4. Plates efficiency

It is well known that power generation in a photovoltaic panel drops as the inner temperature increases. Therefore, it is necessary to consider the losses of the system and compare them with optimized fixed systems (with maximum annual energetic gain). This analysis starts from a thermal study of the system. It considers heat transfer parameters [42,43] next to current–voltage correlations of the photovoltaic panel [44–46]. From the plate model equations, the plate temperature can be calculated at each moment. Nevertheless, the great quantity of cells typologies, and the panel characteristics and configurations, make it difficult to perform a generic study. In this case, several aspects must be remarked:

\[
G_{R0} = I_{SC} \cdot F_R; \quad \text{with} \quad F_R = \frac{1 - \cos \beta}{2}
\]

\[
G_{DD} = I_{DN} \cdot F_D;
\]

\[
F_{D, \text{ isotropic}} = \frac{1 + \cos \beta}{2}
\]

\[
F_{D, \text{ anisotropic}} = (k_b \cdot R_b + (1 - k_b \cdot F_{D, \text{ isotropic}})) \cdot (1 + f \cdot \sin(0.5 \cdot \beta)^3)
\]

with \( f = \frac{I_b}{I_{DN}}; \quad k_b = \frac{I_b}{I_{DN}} \)

where the location latitude \( \varphi \), the angle of incident radiation \( \theta \), surface azimuth angle \( \gamma \), declination \( \delta \) and extraterrestrial irradiance \( I_0 \) (kW/m²) are additional variables to be considered in the analysis. Their instantaneous values can be easily obtained using expressions available in the literature [32]:

\[
\cos \theta = \sin \varphi \cdot \cos \beta - \sin \delta \cdot \sin \theta \cdot \sin \beta \cdot \cos \gamma \\
+ \cos \delta \cdot \sin \varphi \cdot \sin \beta \cdot \cos \omega \\
+ \cos \delta \cdot \sin \varphi \cdot \sin \beta \cdot \cos \gamma \cdot \cos \omega + \cos \delta \cdot \sin \beta \cdot \sin \gamma \cdot \sin \omega
\]

\[
\gamma = \text{sign}(\omega) \cdot \cos^{-1} \left( \frac{\cos \theta \cdot \sin \varphi - \sin \delta}{\sin \theta \cdot \cos \varphi} \right)
\]

\[
\delta = 23.45 \sin \left( 2 \pi \cdot \frac{284 + n}{365} \right)
\]

\[
I_0 = I_{SN} \cdot \cos \theta
\]
(d.2) In a fixed system (south positioned) a high value of the incident angle (corresponding to a low value in the beam component), considerably increases the efficiency. Differences can reach up to 25% during the sunset and the sunrise [43]. Nevertheless, these differences disappear quickly, as the beam component increases.

(d.3) In addition, for an incident angle close to 0°/C176, the cell temperature increases considerably (up to 70°C in conventional cells) while the efficiency decreases. Nevertheless, the relative differences are small (up to 10%) [43]. Thus, the minimum efficiency is reached for high temperatures and high beam component. It is only 10% lower when considering a typical conditions scenario. In a fixed system, this condition is reached around the solar midday, and a similar situation (with higher incident angle and less beam component of radiation) is repeated during most of the solar time. Thus, the difference between fixed and tracking systems will be always less than 10%. In any case, the distribution of the efficiency along the day has been obtained from the reviewed literature, following the tendencies that appear in Fig. 5. The first source (time step motion of item a) must be incorporated to the \( G_{CO} \) determination. Thus, the second and third sources, that is, those indicated in items (b and c), imply that the global irradiance \( G_{CO} \) can be achieved and always will be less than \( G_{CO} \). Subsequently, the effectiveness of the system \( \eta_e \) (see item d) defines the instantaneous electrical production \( W \). These instantaneous data must be integrated, providing a value of the energy response from the device \( J_{day}(n) \) (kWh m\(^{-2}\) day\(^{-1}\)) for the day \( n \) in study, as Fig. 2 shows. The addition of all these daily values along the 365 days of the year provides the annual energy response of the tracked surface \( J \) (kWh m\(^{-2}\) year\(^{-1}\)).

The method is validated for a particular location in the next section. From this analysis it will be possible to obtain several parameters that can be used in a simplified methodology that can be extended for all the cities analyzed in the current work.

3. Detailed local results for one location

The global procedure previously described will be detailed for one particular location: Jaén. The historical Database CENSOLAR provides a value of 5.8 GJ/m\(^2\) for yearly irradiation, while the integration of the instantaneous measurements along 2008 of MatRas group is 5.2 GJ/m\(^2\) (difference around 10%). This analysis has been carried out for instantaneous data along the year.

3.1. Optimum tilt for fixed system

Following the steps described above, the established procedures have been carried out [32,33] for different tilts in order to determine the optimum inclination for a fixed system with a maximum...
annual energetic capturing. The maximum value of yearly energy collection corresponds to 30° tilt. In any case, variations of exposures with tilts between 20° and 40° are below 1% of the maximum value. There exists a 3° difference between the optimum slope for annual evaluation considering isotropic model (30°), and the evaluation considering anisotropic model (33°).

3.2. Two axis tracking without restrictions

To improve the energetic optimization, the theoretical limit occurs when the incidence angle of the radiation is always zero. Eq. (2) has been used to determine the irradiance distribution along the day for horizontal surface.

Fig. 6 shows an example for a particular day of the year. The measured instantaneous irradiance over a horizontal surface together with additional predicted values for other conditions has been presented. At that day, the midday solar angle is around 56°. Thus, the tracker tilt at this time is about 34°, very similar to 30° defined for a fixed system, and consequently they provide very similar results (in fact, the irradiance on the cells of the tracker is slightly higher than for the case of a fixed system). It demonstrates that Eq. (2) can be used to infer the instantaneous irradiances.

Once data along the year (with both clear and cloud sky days), have been evaluated, the average annual exposure of a tracked system regarding to the optimum fixed one without restrictions, is around 30% higher with an isotropic model. On the other hand, an anisotropic model provides up to 38%. As plate efficiency is considered with the same value as for fixed system, the lower and the upper limits for the maximum tracking advantage \( \Delta J_0 \) correspond to those values.

3.3. Motion restrictions

Geometric and mechanical limitations of the tracking system could make not possible to reach certain positions, making the angle of incidence to be different from zero in these cases. Therefore, it is necessary to evaluate how these limits affect to the incoming solar energy. An analysis of different combinations of \( \gamma_l \) and \( \mu_L \) for the tracker has been evaluated, resulting in the incoming energetic losses shown in Fig. 7. For example, for \( |\gamma_l| > 95° \) and \( \mu_L > 60° \), annual losses lower than 1% can be assured. This procedure has been repeated in two additional cities, with maximum and minimum latitudes into the country: Oviedo (43.22°N, 5.50°W) and Las Palmas (28.06°N, 15.25°W). Results are very similar, demonstrating that Jaén represents a typical city to evaluate this kind of losses.

3.4. Tracking strategy

For any control system, it is always required to analyze different time intervals in which the tracker will remain blocked. It implies that the angle of incidence of direct radiation differs from zero, resulting in a lower solar isolation, which decreases as the stop
intervals increase. The incoming losses depending on each new strategy must be evaluated. Thus, Fig. 8 shows instantaneous irradiances on the tracker surface for different stop times: 1, 5, 10, 15, 20, 30 and 60 min.

As a result of integrating the instantaneous data throughout a year, the global energetic capture and losses due to this concept can be obtained giving relative results that are always below 0.5%.

Again, this analysis has been extended to both cities with extreme latitudes within the country: Oviedo and Las Palmas, observing very similar results. Thus, several considerations can be remarked:

(i) Losses are almost identical in the three analyzed cities, which leads to consider the analysis in Jaén as very significant. Thus, results can be extrapolated to the rest of the country.
(ii) Stop interval times below 10 min do not introduce significant differences.
(iii) Incoming radiation losses higher than 1% are only possible with stop intervals of 30 min or more.
(iv) The most useful stop time strategy consists on reducing the intervals as the solar time reaches the midday.

3.5. Shadow losses

Shadow analyses must reflect what exposure can be obtained considering different configurations, width–height relations ($L$–$H$) in the tracking systems and their separation. In those cases with high separation distances, exposures correspond to those results without restrictions (for example, 38% for anisotropic model in Jaén). If geometric parameters associated to separation are modified ($X$ and $Y$), the gain percentages can be estimated, such as Fig. 9 shows.

A comparison between both scenarios (isotropic and anisotropic models) shows that reliable distances correspond to those with 8–10% losses (exposure gains related to optimum fixed systems of 28–30%). More detailed studies will be the goal for a future work. In this analysis, an average global gain is needed to estimate the influence of this kind of losses in the whole final annual result.

3.6. Generation energetic losses

From the tracker installation, some results have been presented in Figs. 10 and 11. Fig. 10a shows the measured results for one day obtained using the tracking system (March 25, 2009). In this figure, data have been compared with those measured on horizontal surface and diffuse models for the tracking strategy, considering a 0.14 reference value of effectiveness in the electrical generation system ($\eta_e$) for that particular day. This value has been achieved in order to adjust the generation with the model as much as possible. Results demonstrate that an anisotropic model is closer to evaluations than an isotropic model for that particular case. The ratio between the instantaneous efficiency and that referenced value $\eta_e$ varies as Fig. 10b shows.

On the other hand, Fig. 11a and b shows results in a midday when the system remained in horizontal position due to wind (April 25, 2009), with a reference value of effectiveness of 0.12 in that particular day. In both cases, the integration of curves in Figs. 10b and 11b provides a mean relative efficiency loss of 20%.

After evaluating multiple days with reliable results, these relative efficiency losses vary from 2% to 7.5%, with a mean value of 5%.

3.7. Global results. Towards a simplified methodology

Table 1 summarizes the prediction of gains and losses due to the different sources considered for the case of Jaén.

If the analyzed procedure is extended to a number of localities, it is possible to obtain an idea of the potential of the tracking system. In addition, there are some aspects that are not necessary to be repeated: both stop timing and motion limits can be adopted in order to assure always losses below 1%, as Table 1 shows. Thus, their influence can be removed from the analysis. In this way, an individual analysis can be done considering the long-term evaluation for fixed systems (providing a $F$ value), next to the tracking surface behavior without restrictions. For this particular case a vector containing all those daily gains $J_{day}$ and a yearly value $J_0$ without restrictions can be obtained. It gives a maximum tracking advantage $\Delta J_0$ (%) previously defined (see Eq. (1.b)).

However, shades and generation losses can also be assumed as those indicated in Table 1. All these losses can be easily inferred in an easy way and their mean values can be adopted for all the cases to study. Then, the final tracking advantage $\Delta J$ can be obtained from $\Delta J_0$ considering the percentage losses indicated in Table 1. It implies that it is necessary to modify the initial procedure described in Figs. 1 and 2 as Fig. 12 shows.

Nevertheless, no instantaneous data are known, and the procedure must start with monthly average daily radiation on horizontal surface $H_0$ (kJ/m²). The hourly instantaneous solar estimation for
the mean day of each month of the year incorporates the mean behavior for all the days for that particular month. Jain et al. [49] obtained horizontal instantaneous irradiance from daily values. They inferred better fitting results than expression in Eq. (2), but its use cannot be generalized. Thus, expressions in Eq. (2) are quite affordable [34]. In any case, the values correspond to average irradiation, integrated from a large amount of instantaneous measurements along the time (usually during some years). In addition, the adopted models consider statistical analyses from all these data [17,32]. It means that models account for the weather conditions for both cloudy and clear days.

In this sense, the analysis without restrictions has been repeated for the case of Jaén, starting now from published HG values [15]. Although final annual irradiation is slightly different for both cases, the main task to remark is that the difference between the gain ratios is below 1%. For the case of an anisotropic model, $D_{J0}$ was obtained from instantaneous data, providing a value of 38.5%, while when using monthly average daily radiation the value was 37.97%. It demonstrates that the proposed procedure can be efficiently used when employing monthly average daily radiation values.

4. Global estimation results along the country

Therefore, the indicated procedure has been carried out for all the main cities in Spain (52). There are three locations that belong to island territories, and two national cities into African continent (next to Morocco). The other 47 cities are distributed into the peninsular territory. Thus, the geographical locations approach can be seen in Fig. 13.

Annual results from integration of instantaneous daily data can be observed and compared throughout the $D_{J0}$ term in Fig. 14.

There are some conclusions that it is possible to extract from Fig. 14: optimum tilt for fixed systems implies an exposure respect to horizontal surface that ranges between 5% and 20%. However, a
tracking system implies an exposure that ranges between 27% and 40% (anisotropic model), or between 22% and 33% (isotropic model). These differences vary between 5% and 8% depending on the diffuse model. Therefore, three different scenarios can be deduced: pessimist, associated with the isotropic model; optimistic, associated to the anisotropic model, and in addition, an average or moderate scenario with intermediate values between the two previous ones.
In all the cases, tendencies follow exponential laws. These trends are not related only to the latitude. Cities placed in the coastal top band of the country next the Cantabric Sea, originate worse results, not only for its latitude, but for the minor irradiation that takes place in them, principally diminished by the proximity to the sea and a major rainfall. It has not been reflected so drastically in the Pyrenean area (French border) with similar latitudes.

The main conclusion is that for a moderate scenario, two axes tracking systems assure a 30% of gain over a fixed system in the major of the country. In an optimistic scenario (anisotropic model), it can be assured that this limit would reach a 35% value.

All the losses related to the limitations of the system (motion limits, control, shadows, etc.) have been incorporated into the previous results without restrictions, obtaining an estimation of the electric production. Thus, in Fig. 15 it can be observed all these situations throughout $\Delta J$, depending on latitude of the cities.

Economical approaches indicate there exist a 15–20% additional costs in tracking systems compared to fixed ones, due to higher investments, as well as other costs associated with the operation and maintenance of the plant (usually related to the electricity production). Thus, locations with an energy advantage $\Delta J$ higher than 20% (see Fig. 15) can experience a better profitability if a tracking system is considered instead of a fixed one.

It can be observed that two axes tracking systems can be in 37 of the 52 main cities in Spain. Nevertheless, there are seven cities where these systems are not recommended in any case: A Coruña, Orense, Oviedo, Santander, Bilbao, Vitoria, San Sebastián. There are five additional cities, where some uncertainties also appear: Barcelona, Gerona, Lugo, Pamplona, Las Palmas and Pontevedra. Ten of these cities correspond to the North coastal band of the country.

In all the cases, tendencies follow exponential laws. These trends are not related only to the latitude. Cities placed in the coastal top band of the country next the Cantabric Sea, originate worse results, not only for its latitude, but for the minor irradiation that takes place in them, principally diminished by the proximity to the sea and a major rainfall. It has not been reflected so drastically in the Pyrenean area (French border) with similar latitudes.
while two of them belong to the highest latitudes in the Mediterranean zone. Moreover, Las Palmas belongs to the Canary Islands with low latitude (28.2°). A high humidity and rainfall because of the proximity to the sea, next to the locations latitude could be the main reasons for non-advisable installations in these locations. Results illustrate that in most of the national territory two axes tracking systems seems to be profitable. Obviously, a more detailed analysis in a higher number of locations must be done if gains must be quantified.

5. Conclusions

This work demonstrates that two-axes tracking systems can assure an economic viability respect to fixed ones in most of the Spanish national territory. There are some areas where high humidity, rainfall and latitude combine making not recommendable these solutions.

In any case, this work is a starting point to define a further detailed economic analysis. For this purpose, it is necessary to add some technical details to the present model, such as different field configurations and systems separation (in order to optimize the shadow losses) and detailed instantaneous thermal–electrical model of the plates. It is also necessary to evaluate the investment costs in detail, by evaluating different market solutions, and incorporating the ground field price, in order to reduce the additional investment costs band (as Fig. 14 shows). At this point, investment decision criteria can be adopted, such as the Internal Rate of Return (IRR) of Payback Period (PB), searching the optimum one for a given surface size and separation distances between systems into the trackers field.

Acknowledgments

The authors thank to the University of Jaén (Project Desarrollo y optimización mecánica de un sistema de seguimiento solar de dos ejes para el aprovechamiento energético del olivar jiennense, Code RFC/PP2006) for technical help and financial supports provided. It has made it possible to carry out the presented analyses.

Appendix A. Symbols

\( a, b \) coefficients to \( r_T \) determination (see Eq. (2))
\( F \) annual electricity to the grid (kWh \( \text{m}^{-2} \cdot \text{year}^{-1} \)) for fixed system
\( F_S \) maximum annual solar irradiation (kWh \( \text{m}^{-2} \cdot \text{year}^{-1} \)) for a fixed system
\( f_1, f_2, f_3 \) function to approach \( G_{\text{BO}} \)
\( G_{\text{BO}} \) vector of beam component of irradiance (W/m\(^2\)) on a tracked system
\( G_{\text{DO}} \) vector of diffuse component of irradiance (W/m\(^2\)) on a tracked system
\( G_{\text{GD}} \) vector of global irradiance (W/m\(^2\)) considering only motion limits restrictions for a tracker system
\( G_{\text{GS}} \) vector of global irradiance (W/m\(^2\)) for a tracker system, considering motion limits, shadow losses and plates efficiency
\( G_{\text{GR}} \) vector of reflected component of irradiance (W/m\(^2\)) on a tracked system
\( H \) surface height (m)
\( H_L \) monthly average daily radiation on horizontal surface (kJ \( \text{m}^{-2} \cdot \text{day}^{-1} \))
\( H_L' \) hourly irradiation (time \( j \)) from \( H_L \) (kJ \( \text{m}^{-2} \cdot \text{h}^{-1} \))
\( I_b \) beam component of irradiance over horizontal surface (kW/m\(^2\))
\( I_D \) diffusive component of irradiance over horizontal surface (kW/m\(^2\))
\( I_G \) global irradiance over horizontal surface (kW/m\(^2\))
\( I_{\text{BO}} \) extraterrestrial irradiance (kW/m\(^2\))
\( I_{\text{SN}} \) solar constant (kW/m\(^2\))
\( J \) annual electricity to the grid (kWh \( \text{m}^{-2} \cdot \text{year}^{-1} \)) for a tracking device
\( J_0 \) annual electricity to the grid (kWh \( \text{m}^{-2} \cdot \text{year}^{-1} \)) for a tracking device without restrictions
\( J_{\text{day}} \) daily electricity to the grid (kWh \( \text{m}^{-2} \cdot \text{year}^{-1} \)) for a tracking device
\( J'_{\text{day}} \) daily electricity to the grid (kWh \( \text{m}^{-2} \cdot \text{year}^{-1} \)) for a tracking device without restrictions
\( k_t \) instantaneous clearness index (dimensionless)
\( L \) surface width (m)
\( N \) length of vector \( T \) (number of components)
\( r_T \) ratio of hourly total to daily total radiation
\( T \) time vector for daily analyses (from sunrise to sunset)
\( T_{\text{STOP}} \) time stop vector for daily analyses (from sunrise to sunset).

Indicates when the tracker changes its position along the time
\( W \) electrical production of a tracked system (W/m\(^2\))
\( \alpha_5 \) solar altitude angle (deg)
\( \beta \) instantaneous tilt for a tracking system (deg)
\( \beta_L \) maximum tilt that a tracking system reaches (deg)
\( \beta_{\text{opt}} \) optimum tilt for a fixed system to assure maximum solar capturing (deg)
\( \gamma \) surface azimuth angle (deg)
\( \gamma_{\text{abs}} \) absolute value of maximum surface azimuth angle that tracking system reaches (deg)
\( \gamma_{\text{opt}} \) solar azimuth angle (deg)
\( \eta_e \) average electricity generation efficiency for a tracked system (dimensionless)
\( \eta_{\text{ef}} \) average electricity generation efficiency for a fixed system (dimensionless)
\( \vartheta \) angle of incidence of radiation (rad)
\( \vartheta_Z \) zenith angle (rad)
\( \omega \) sun hour angle (rad)
\( \omega_S \) sunset hour angle (rad)
\( \varphi \) latitude angle (deg)
\( \delta \) declination (deg)
\( \sigma \) reflectance coefficient (dimensionless)
\( \Delta J_0 \) maximum tracking advantage: annual relative gain in electrical production of a tracking system without restrictions respect to a fixed one (%)
\( \Delta J \) tracking energy advantage: annual relative gain in electrical production of a tracking system respect to a fixed one (%)

References
