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Methodology for the estimation of cultivable space in photovoltaic installations with dual-axis trackers for their reconversion to agrivoltaic plants

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HIGHLIGHTS

- A model to define cultivable space between two-axis solar collectors is presented.
- For the study case, pentagonal street profiles for cultivation have been identified.
- The 74% of the land between collectors is cultivable for crop under 1.4 m high.
- This work boosts the possible agrivoltaic reconversion of existing 2-axis PV plants
- This work lets optimize synergies between crop and PV in agrivoltaic plants.

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ABSTRACT

Agrivoltaics or dual use of land for agricultural production systems and photovoltaic energy is experiencing a significant boom since it favours the sustainability and efficiency of both systems, while helping to alleviate the conflict over land use and protecting rural economies. In this context, it is essential to study possible combinations between photovoltaic installations and agricultural operations that optimize the synergies between both production systems. Specifically, since solar irradiance is the common resource shared by both systems, it is necessary to find a balanced distribution of the solar energy to protect agriculture. This work simulates the behaviour of solar irradiance and its interaction with photovoltaic panels and the crop, as well as possible shading, in a photovoltaic plant to study its potential reconversion into an agrivoltaic installation. From this analysis, an innovative methodology is defined to determine the space between the collectors in which the levels of solar irradiance received would be sufficient for adequate crop development. Specifically, the method has been applied to simulate "El Molino" plant, a photovoltaic facility located in Córdoba, Spain with two-axis (azimuthal and elevational) solar trackers and backtracking. For this facility, pentagonal arable streets between the collectors have been identified. Specifically, along the N-S direction these pentagonal areas have a width of 10.5 m, a minimum height of 1.31 m in the lateral areas and a maximum height of 2.81 m in the central. Accordingly, different proposals for crop occupation have been proposed. Likewise, the curve of the percentage of maximum cultivable area as a function of the crop height has been represented, obtaining that for crops with a height of 1.4 m up to 74% of the land between collectors is arable, decreasing this space as the height of the crop increases. Thus, this work represents progress in the possible reconversion and agrivoltaic use of large existing photovoltaic plants, improving their sustainability and contributing to the necessary deployment of agrivoltaics and the fight against Climate Change.

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Nomenclature

φ	latitude
δ	solar declination
Ω	angular rotation speed of the Earth
t	time with respect to solar noon
a	width of the solar collectors or length of its lower edge (horizontal)
b	height of the solar collector or length of its edge on the direction of maximum inclination
h_T	height of pole supporting the photovoltaic collectors
A	lower right corner of the collector
B	lower left corner of the collector
AB	lower edge (horizontal) of the solar collectors
γ	azimuth of the solar collectors
α	elevation of the solar collectors
P_0	location of the foot of the reference collector
i	index to referred to the PV collector under study.
P_i	location of the foot of the collector under study
P	each of the study points considered in the land
T and T'	points of tangency of the boundary band with the solar collectors in the case of backtracking
h_c	maximum permissible crop height for a point P at a given instant of time.
$\vec{i}$	unit vector associated with the Ox axis oriented towards the West
$\vec{j}$	unit vector associated with the Oy axis oriented towards the South
$\vec{k}$	unit vector associated with the Oz axis oriented towards the zenith
$\vec{s}$	solar vector or unit vector directed towards the solar disk at all times.
$\vec{n}$	unit normal vector to the collectors
$\vec{u}$	unit vector on the direction of the lower edge of the collector plane (horizontal)
$\vec{v}$	unit vector on the direction of maximum inclination of the collector plane
$\overrightarrow{P_0P_i}$	vector from the foot of the reference collector to the foot of the collector under study i
(x_f, y_f, z_f)	coordinates of the point P
(x_A, y_A, z_A)	coordinates of the point A
(u_x, u_y, u_z)	components of vector $\vec{u}$
(v_x, v_y, v_z)	components of vector $\vec{v}$
(s_x, s_y, s_z)	components of vector $\vec{s}$
λ and μ	study parameters to determine whether a terrain point P is limited in height.

1. Introduction

In recent years, agrivoltaics has been presented as a possible solution to some of the great challenges that society faces today. It is defined as the shared use of land for agricultural and photovoltaic production [1], allowing us to simultaneously satisfy the demand for food and energy, which has been experiencing significant growth in recent years due to the increase in world population. Furthermore, agrivoltaics contributes to the fight against Climate Change [2,3] and drives progress towards a more sustainable planet by promoting more efficient and environmentally friendly energy and agricultural production systems [4].

On the other hand, the deployment of photovoltaics has caused large plots of agricultural land to be converted into grid-connected photovoltaic plants [5], based on the greater profitability of photovoltaic production compared to that of most agricultural crops. However, this transformation brings with it notable dangers for the environment (loss of biodiversity and threat to some animal species), food security (difficulty in food supply), the rural economy (loss of agricultural employment, settlement of rural areas) and the quality of life of the inhabitants of those areas where the natural landscape is replaced by photovoltaic plants [5–11]. As a consequence, more and more groups reject the advance of photovoltaics in its current model and request the implementation of renewable energies that do not pose a threat to the environment [12–14]. In this regard, agrivoltaics helps to alleviate the conflict over land use [2,6,15] by making photovoltaic and agricultural production compatible.

From the agricultural point of view, various studies have proven that photovoltaic panels provide protection to crops against high levels of solar irradiance, high temperatures [4,16–20] and even against adverse meteorological phenomena such as hail or wind [6,21]. Furthermore, the reduction of solar irradiance and temperature on the crop land [22] reduces water consumption through evapotranspiration [4,23,24], which benefits the soil water balance [17,25]. According to this, the shade collectors provide in agrivoltaic systems benefits crops in extreme conditions of heat and drought [4,16,17,23–25], strengthening agriculture against the negative consequences of Climate Change [6,16,17]. In addition, from the photovoltaic point of view, the crop moisture helps to reduce the temperature in the photovoltaic cells and, as a consequence, improves the performance of the photovoltaic system [26,27].

Likewise, from an economic point of view, agrivoltaics helps to increase the overall income of farmers by adding agricultural and energy benefits [18,24,28–31]. In addition, income sources are diversified while their dependence on the weather is reduced [6,31]. Therefore, agrivoltaics can help alleviate the effects of the crisis that the agricultural sector has been experiencing in recent years.

As a consequence of all these advantages there is a growing interest worldwide in agrivoltaics, resulting in various countries developing government programs that support and promote agrivoltaics to a greater or lesser extent [32,33]. Thus, agrivoltaics is experiencing significant growth and in the last decade the photovoltaic capacity installed in agrivoltaic plants worldwide has increased from 5 MWp installed in 2012 to more than 14 GWp in 2021 [6].

This growth in interest in agrivoltaics has also led to the advancement of the technologies used in these types of facilities. Thus, for example, although the first agrivoltaic plants were limited to those with photovoltaic installations with fixed panels [24], other designs with solar trackers, both single-axis and dual-axis, have recently been implemented [16,17,20,25,28,29,34]. As an example of the latter, “Huerto Carrasco” and “Huerto del Hito” plants, both in Fuentealbilla (Albacete, Spain), combine vineyard planting (6.6 ha) and plum trees (13.1 ha) with collectors installed on dual-axis solar trackers with a capacity of 0.9 MW and 1.8 MW of installed power, respectively. It is important to point out that, although at the time of the writing of this paper there is no Spanish legislation regulating agrivoltaics in the country, according to the definition of agrivoltaics, these installations make photovoltaics and agriculture compatible, with special emphasis on the protection of agriculture as the main productive activity of the farm [1]. Furthermore, the characteristics of these plants meet the conditions imposed for agrivoltaic plants in the regulations existing in countries around Spain, such as Italy and Germany [35–39].

It has been proven that the use of solar trackers in agrivoltaic installations improves both the production of the photovoltaic plant [28] and the crop [20,25,28,34]. Specifically, solar trackers, in addition to protecting the crop from inclement weather, improve the distribution of rain on the crops under the panels [29]. Likewise, the use of solar trackers allows increasing solar irradiance on PV panel surfaces at extreme hours of the day and reducing high temperatures at midday [28] or adjusting the orientation of the solar collectors throughout the year and regulating shadows and solar irradiance levels to the needs of the crop at all times, optimizing growth [20,25,28,29]. This measure, although it could result in lower electricity production, would be beneficial for the crop and would favour an adjusted balance between both productions. Consequently, new specific solar tracking strategies for agrivoltaic systems are being developed [40,41].

According to this, it is necessary to advance scientific knowledge of the behaviour of agrivoltaic systems with solar tracking. Specifically, in these types of facilities it is essential to study the interaction between solar irradiance, crop and photovoltaic collectors to find an optimal balance between the two production systems involved (agricultural and photovoltaic) that is not based on merely economic criteria, but rather protects agricultural production. To do this, it is necessary to consider crop needs for solar irradiance for photosynthesis or its light saturation point [6]. Therefore, it is essential to simulate and estimate the percentage of shadow projected by the solar collectors on the crop as well as the levels of solar irradiance available in an agrivoltaic installation based on the characteristics and spatial distribution of the photovoltaic collectors as well as the type of solar tracking, if they have it [42].

In this line of work, Casares et al. [43] simulated the behaviour of solar irradiance in a possible agrivoltaic plant in which a photovoltaic installation with tracking of a horizontal North-South (N-S) axis and a tree crop in hedges also planted in the N-S direction between the rows of collectors are combined. As a result of this study, the authors found that there is a geometric space between the rows of photovoltaic panels in which the crop would not shade the latter. As a consequence, crop-growing does not affect the solar tracking strategy or photovoltaic production. Likewise, the work proposes a new tracking/backtracking strategy to avoid shadows on the photovoltaic panels when the crop exceeds this region of no influence. The energy production of this type of agrivoltaic plant was also simulated, demonstrating its economic viability.

With this in view, from the theoretical study of the solar astronomy equations and the geometry of the photovoltaic plant under studio, the present work aims to simulate and characterize the behaviour of solar irradiance in agrivoltaic plants in which photovoltaic panels are installed on dual-axis solar collectors. Based on this analysis, an innovative method is proposed to estimate the maximum available space that could be occupied by crops within photovoltaic plants with rectangular collectors on dual-axis trackers (azimuthal and elevational) with backtracking. Once this maximum available area is known, it will be necessary to select the most suitable crop according to the characteristics of the crop and its exploitation requirements. The final yield of the agricultural installation will depend on the crop selected. The study focuses on the possibility of arranging crops in hedges, groups of hedges or rows of trees with known crown geometry.

2. Methodology

2.1. Sun-earth astronomy

In accordance with the objective of the work, to develop the proposed study, it is essential to establish a valid reference system for any location such as the one represented in Fig. 1. In addition, it is necessary to define the vectors that characterize the system under study in this reference system. This system considers its Ox axis oriented towards the West, the Oy axis oriented towards the South and the Oz axis oriented towards the zenith of the place, with $\overrightarrow{i}$, $\overrightarrow{j}$ y $\overrightarrow{k}$ being the unit vectors associated with the Ox, Oy and Oz axes respectively.

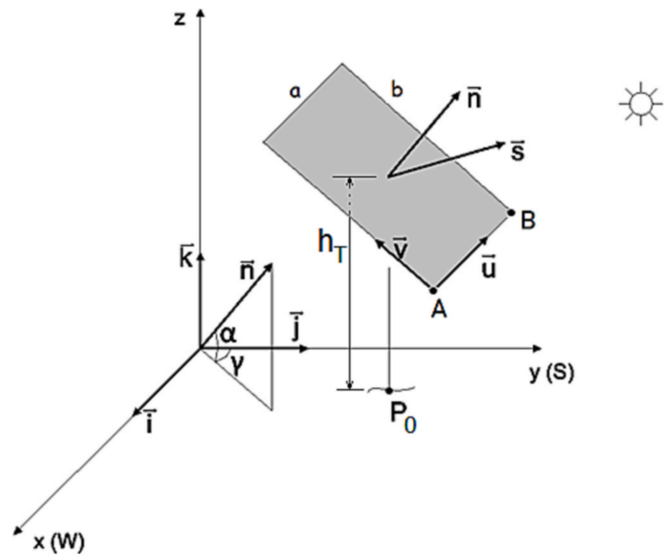

Fig. 1. Representation of the collector surface in the Earth reference system.

Considering the values of the latitude of the place (φ), the solar declination (δ) and the hour angle (Ωt) given by the product of the angular rotation speed of the Earth ($\Omega = 2\pi/24 rad/h$) and the time t with respect to solar noon, the vector solar $\overrightarrow{s}$, that is, the unit vector directed towards the solar disk at all times, can be defined by Eq. (1).

$$\overrightarrow{s} = s_x\overrightarrow{i} + s_y\overrightarrow{j} + s_z\overrightarrow{k} = (sin\Omega t\ cos\delta)\overrightarrow{i} + (cos\Omega t\ cos\delta\ sin\varphi - sin\delta\ cos\varphi)\overrightarrow{j} + (cos\Omega t\ cos\delta\ cos\varphi + sin\delta\ sin\varphi)\overrightarrow{k} \tag{1}$$

Furthermore, once the azimuth γ and the elevation α of the solar collectors are known, it is possible to determine the unit normal vector $\overrightarrow{n}$ to the surface of the collectors at each instant using Eq. (2) valid for the reference system indicated in Fig. 1. Likewise, Eqs. (3) and (4) allow obtaining the unit vectors $\overrightarrow{u}$ and $\overrightarrow{v}$, mobile and solidary with the collector plane, with $\overrightarrow{u}$ being the horizontal unit vector with the same direction as the lower edge of the collector rectangle and $\overrightarrow{v}$ the vector unitary in the direction of maximum inclination of the collecting plane, a direction that coincides with that of one of the sides of the collecting rectangle.

$$\overrightarrow{n} = cos\alpha \bullet sin\gamma\overrightarrow{i} + cos\alpha \bullet cos\gamma\overrightarrow{j} + sin\alpha\overrightarrow{k} \tag{2}$$

$$\overrightarrow{u} = -cos\gamma\overrightarrow{i} + sin\gamma\overrightarrow{j} \tag{3}$$

$$\overrightarrow{v} = sin\alpha \bullet cos\gamma\overrightarrow{i} - sin\alpha \bullet cos\gamma\overrightarrow{j} + cos\alpha\overrightarrow{k} \tag{4}$$

2.2. Tracking-backtracking

Once the characteristic vectors of the study have been defined, it is necessary to analyse their behaviour as a consequence of the movement of the collectors that depends on the position of the Sun at each instant. To this end, in previous works [44,45] the authors have presented a rational method to obtain the azimuth γ and the elevation α at each moment of the year for the solar trackers of grid-connected photovoltaic facilities so that the incidence of irradiance on the modules is maximized and no collector overshadows another.

Basically, for regularly spaced trackers, a representative tracker, generally central, is considered (Fig. 2) and the set of vectors $\overrightarrow{P_0P_i}$ that join the center of the foot of this reference collector or point P_0 with those of the remaining collectors is analysed. It is shown that at a certain

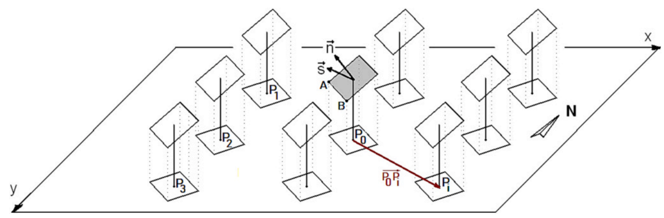

Fig. 2. Representation of points and vectors to check if a direction of the collectors, given by $\overrightarrow{n}$, generates shading between collectors.

instant of time, a collector orientation given by the vector $\overrightarrow{n}$ does not produce shading if for the set of vectors $\overrightarrow{P_0P_i}$ that meet the condition expressed by Eq. (5), and simultaneously one of the inequalities (6) or (7).

$$\overrightarrow{P_0P_i} \bullet \overrightarrow{s} > 0 \tag{5}$$

$$\left| \left(\overrightarrow{P_0P_i} - \frac{\overrightarrow{P_0P_i} \bullet \overrightarrow{n}}{\overrightarrow{s} \bullet \overrightarrow{n}} \overrightarrow{s} \right) \bullet \overrightarrow{u} \right| > a \tag{6}$$

$$\left| \left(\overrightarrow{P_0P_i} - \frac{\overrightarrow{P_0P_i} \bullet \overrightarrow{n}}{\overrightarrow{s} \bullet \overrightarrow{n}} \overrightarrow{s} \right) \bullet \overrightarrow{v} \right| > b \tag{7}$$

Thus, for each moment of the year, there is a value of $\overrightarrow{s}$ and a set of values of $\overrightarrow{n}$ for which intershading does not occur. The authors recommend choosing the one that maximizes the irradiance on the reference collecting plane. In this phase two possibilities can be distinguished:

(a) the optimal collector position, that is, the one that maximizes the direct irradiance, is within the set of values of $\overrightarrow{n}$ that do not produce shading. At this moment astronomical tracking is carried out and the orientation of the tracker will be made to coincide with $\overrightarrow{n} = \overrightarrow{s}$.
(b) The orientation that maximizes the direct irradiance in the sky is not within the set of values of $\overrightarrow{n}$ without shading. At these moments the tracker performs backtracking by choosing an orientation among those that do not generate shading.

However, as mentioned above, these previous works [44,45] focuses on the study of grid-connected photovoltaic plants without dual land use. Therefore, in order to extrapolate this methodology to agrivoltaic plants, it is also necessary to consider the interaction with the crop, which has been ignored until now, being this the objective of the present work.

2.3. Proposed method

Accordingly, this section specifically describes the method for identifying the non-shading zones between the two-axis solar trackers in agrivoltaic plants. For that purpose, the flat strips obtained when moving the lower segment of the collector, AB, parallel to vector $\overrightarrow{u}$, along the direction of the solar vector are considered. The non-existence of mutual shading between collectors due to backtracking ensures that the mentioned flat strips do not intercept other collectors at any time. Thus, it is possible to affirm that the space freely usable by crops must necessarily be found below these boundary bands.

For those strips, two situations must be considered. The first situation under study correspond to those instants when the sun is high enough in the sky vault so that there is no inter-shading between solar collectors and the reference solar collector is performing astronomical tracking. At these moments the collector points towards the sun ($\overrightarrow{n} = \overrightarrow{s}$) and the boundary strip rises towards the sun without touching other collectors.

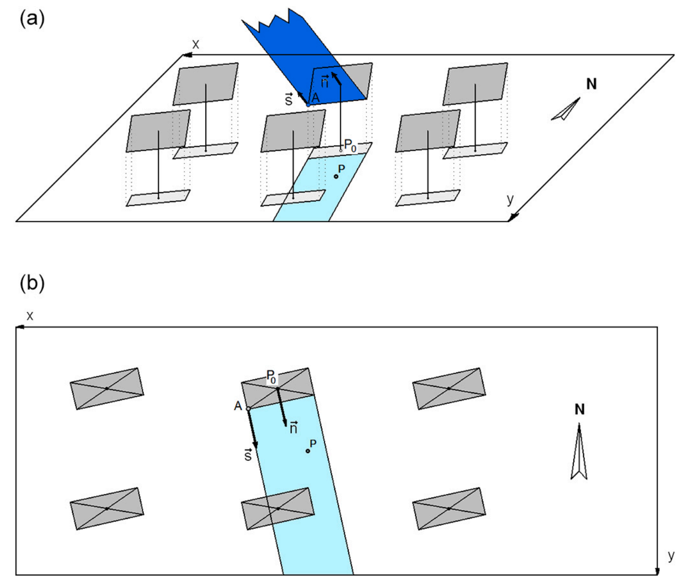

Fig. 3. Representation of the strip below which the vegetation must remain so as not to shade the reference collector (dark blue strip) and its orthogonal projection (light blue strip): (a) Three-dimensional view of the strip at a time when the collector is performing solar tracking; (b) Plan view of the three-dimensional situation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3 shows the boundary strip in dark blue and its orthogonal projection on the ground in light blue for a situation of astronomical tracking. Thus, the area included in the light blue strip will be limited in hight by the dark blue strip.

However, when inter-shading between collectors would occur, to avoid it, the reference collector performs backtracking. At these times the reference collector is not pointing towards the sun ($\overrightarrow{n} \neq \overrightarrow{s}$) and the boundary strip is tangent at the points T and T' to the rectangle of another collector. Fig. 4 shows the boundary strip in dark blue and its

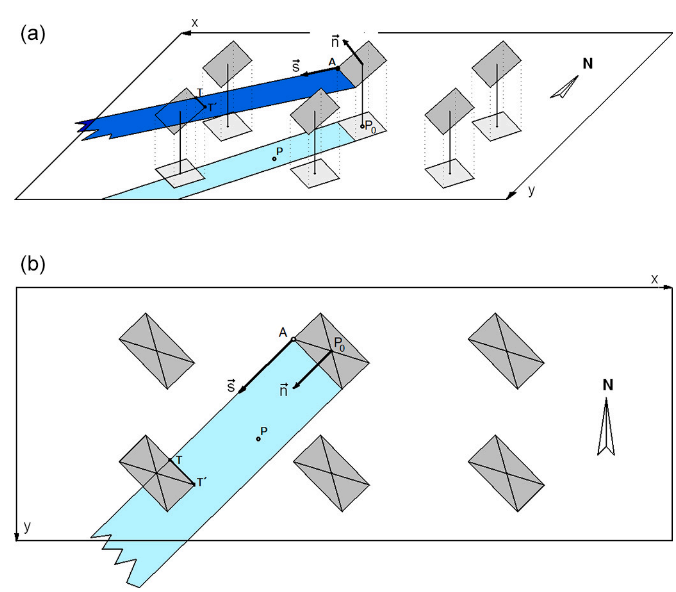

Fig. 4. Representation of the strip below which the vegetation must remain so as not to shade the reference collector (dark blue strip) and its orthogonal projection (light blue strip): (a) Three-dimensional view of the strip at a time when the collector is performing backtracking; (b) Plan view of the three-dimensional situation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

orthogonal projection on the ground in light blue for this situation of backtracking. Once again, the area included in the light blue strip will be limited in hight by the dark blue strip.

According to the geometry of the problem under study, from the foot of the reference collector it is possible to define the lower right vertex of the collector, A, with coordinates (x_A, y_A, z_A), by Eq. (8) where h_T represents the height of the pole supporting the reference collector located at P_0 (Fig. 5).

$$\begin{Bmatrix} x_A \\ y_A \\ z_A \end{Bmatrix} = \begin{Bmatrix} x_{P_0} \\ y_{P_0} \\ z_{P_0} \end{Bmatrix} + h_T \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix} - \frac{a}{2} \begin{Bmatrix} u_x \\ u_y \\ u_z \end{Bmatrix} - \frac{b}{2} \begin{Bmatrix} v_x \\ v_y \\ v_z \end{Bmatrix} \tag{8}$$

Thus, for each instant of time, once the limit band has been obtained, it is necessary to determine whether the different points P, of a regular grid of points distributed over the terrain, are affected by these boundary bands. Specifically, according to Fig. 6, the affected points P will be those points included in the light blue band; that is, those which, verify the conditions (10) and (11) when solving the Eq. (9). For these points included in the light blue band, the maximum height that a crop could have will be that of the vertical from P to the dark blue band, given by h_c in Eq. (9).

$$\begin{Bmatrix} x_P \\ y_P \\ 0 \end{Bmatrix} + h_c \begin{Bmatrix} 0 \\ 0 \\ 1 \end{Bmatrix} = \begin{Bmatrix} x_A \\ y_A \\ z_A \end{Bmatrix} + \lambda \begin{Bmatrix} u_x \\ u_y \\ u_z \end{Bmatrix} + \mu \begin{Bmatrix} s_x \\ s_y \\ s_z \end{Bmatrix} \tag{9}$$

$$0 \le \lambda \le a \tag{10}$$

$$\mu \ge 0 \tag{11}$$

By extending this criterion to the different moments of the astronomical year, it is understood that the searched surface must be the lower envelope of all the bands generated at all moments of the astronomical year.

3. Results

This section shows the results of applying the proposed methodology in "El Molino" photovoltaic installation located in Córdoba, Spain (latitude 37.75492 N; longitude 5.04548 W). It is a plant with dual-axis rectangular collectors 8 m wide, 5 m long and 3.5 m high ($a = 8m, b = 5m, h_T = 3.5m$) (Fig. 7). Tracking is carried out on a primary azimuthal axis and a secondary elevational axis. In this way the lower side of the collector rectangle remains horizontal at all times. The collectors are arranged in a regular grid with East-West equidistance $d_{EW} = 20\ m$ and North-South distance $d_{NS} = 14\ m$.

The procedure for obtaining the envelope or set of points that always

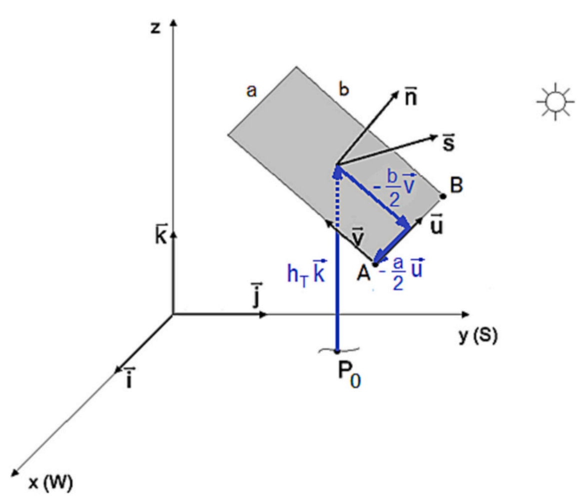

Fig. 5. Geometric representation of the vectors involved in Eq. (8).

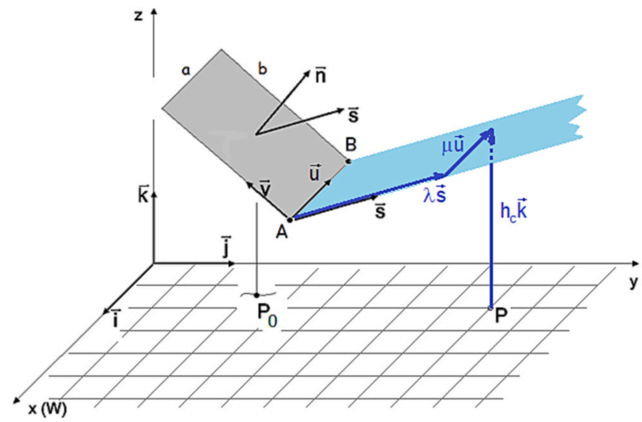

Fig. 6. Geometric representation of the vectors involved in Eq. (9).

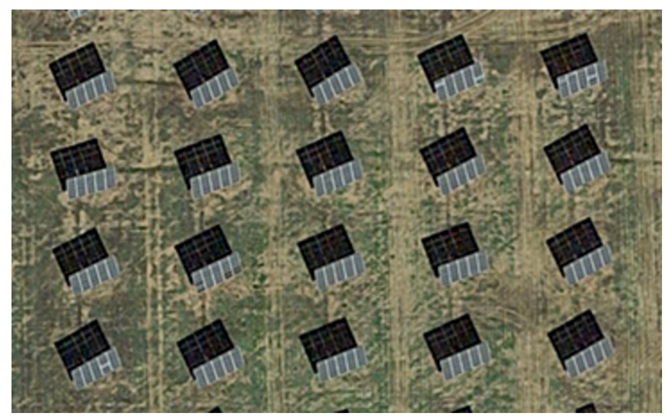

Fig. 7. Aerial photography of "El Molino" installation (Source: Google Maps).

remains below the limit bands has been structured in two phases. In the first phase, this envelope is determined in the space surrounding a single typical collector. The envelope thus obtained constitutes a surface associated with the reference tracker. Fig. 8 shows the surface obtained in the first phase for a reference tracker.

It shows that the envelope for the reference collector is not defined for a sector located to the north of the collector (represented in blue), since the boundary bands that have emerged from the reference tracker are never found on this surface. Likewise, the grey circle centred on the base of the reference tracker (P_0) represents the surface necessary for the movement of the tracker and where the possible vegetation would collide with its plane.

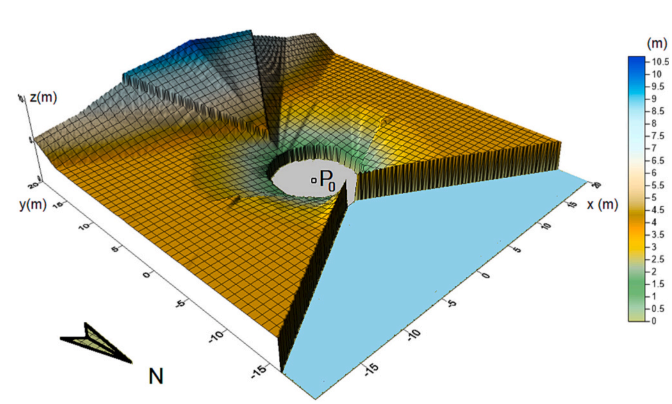

Fig. 8. Permissible vegetation envelope for the reference collector in the case of "El Molino" photovoltaic installation.

Three sectors can be seen on the surrounding surface, two symmetrical ones located to the East and West of the reference point and one sector located to the South. The shape of the East and West sectors is conditioned by tracking-backtracking. Thus, the areas far from the reference point are markedly horizontal and close to the height of the tracker shaft. This is because at the beginning and end of the day the tracker is practically horizontal and at a height close to that of the shaft. At these times the boundary bands are very horizontal and produce the indicated plateaus. In the vicinity of the collector within the East and West zones, a hollow can be seen centred on the collector. This is due to the fact that the emerging bands at times when solar tracking begins start from the levels on the lower side of the collector, which are at heights of 1.5 m. In the southern sector, the existence of a promontory can be seen, which is due to the fact that at midday the collector follows solar tracking, with very inclined emerging bands due to the fact that the sun is close to its culmination, which gives rise to the elevation of the surface.

In the second phase, to obtain the global envelope of the set of collectors, the patterns corresponding to each tracker must be superimposed. From the set of superimposed patterns, as if each tracker were the reference, and for each point on the horizontal plane, the lowest of the heights of the different individual patterns must be considered. For the case studied, this phase gives rise to the envelope represented in Fig. 9. It can be seen that the resulting pattern is basically composed of a series of depressions centred on each collector allowing the existence of 3.5 m high zones in a position immediately to the North of each tracker that in Fig. 9 coincides with the pinnacles, and other areas 3.5 m high located between every 4 collectors. The analysis of the surface obtained allows studying the possibility of establishing crops with a regular implantation pattern under this surface.

It is important to note that the computing time required to obtain Fig. 9 on an Intel(R) Core(TM) i5-8250U CPU 1.80 GHz computer is 576 s. Therefore, it can be stated that this is a useful method applicable to different configurations of photovoltaic plants without high computational demands.

4. Discussion

From the results of the simulation, it is possible to determine the space between collectors available for crops in “El Molino” photovoltaic installation. Specifically, with regard to the possibility of crops in a N-S arrangement, the envelope obtained and represented in Fig. 9 allows

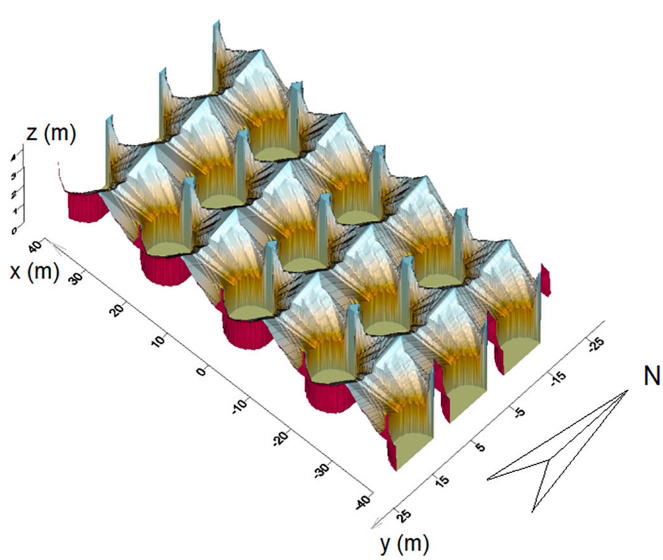

Fig. 9. Global envelope of permissible vegetation in the “El Molino” photovoltaic installation.

delimiting the possible crop hedges in this direction, establishing as a condition that these hedges would not interfere with solar tracking policies.

To visualize and calculate the possible dimensions of these hedges, Fig. 10 shows a new representation of the envelope but projected on the Oxz plane. It shows the existence of some spaces with a N-S orientation where arable hedges could be placed as long as their profiles were circumscribed by the N-S corridors represented. Fig. 10 shows that trapezoidal profile streets constitute the design space of the cultivation geometries where a hedge or spherical crop could be cultivated (it must be considered that in Fig. 10 the difference in magnitude of the scales causes the spheres to be projected as ellipses). The cylindrical volumes appearing as columns in Fig. 10 correspond to the collision spaces with the collector planes.

For greater clarity in Fig. 11a, the usable space between collectors is represented for cultivation, and the dimensions of the rows are bounded using the same scale for both the horizontal and vertical axes. It can be seen that the trapezoidal profile streets available for cultivation have a width of 10.5 m, a minimum height of 1.31 m in the lateral areas and a maximum height of 2.81 m in the middle area. Additionally, as an example, different proposals for crop occupation in N-S alignments are represented: the profile of a 2.65 m tall and 1.5 m wide hedge (suitable for hedgerow olives) (Fig. 11b), a row of spherical-crowned trees with a 2.5 m diameter and 25 cm trunk (suitable for fruit trees) (Fig. 11c), and rows of 1.7 m in height and 0.6 m width separated by 3.5 m (suitable for vineyards) (Fig. 11d).

Similarly, crop alignments can be characterised in an *E*-W direction. To do this, the surface represented in Fig. 9 is projected onto a vertical plane with a N-S direction (Fig. 12). This figure illustrates the existence of pentagonal cross-sectional clear corridors, although it is important to note that, in this view, the vertical and horizontal scales are different.

Fig. 13a provides a more detailed view, using the same scale on the vertical and horizontal axes, of the dimensions of the available clear spaces in the E-W direction. It can be observed that these spaces are smaller than those in the N-S direction. However, they would still allow for the placement of olive hedges, rows of spherical-crowned fruit trees, and vineyards, as depicted in Fig. 13b, c, and d, respectively.

Thus, for the case under study, that is, “El Molino” plant, the pentagonal profile streets in the N-S and E-O directions, as represented and dimensioned in Figs. 11 and 13, respectively, constitute the design spaces available for crop geometries. On the basis of this geometry, it will be necessary to select the most suitable crop for the same and the agro-climatic conditions and availability of the solar resource, which will condition the agricultural production of the installation and, therefore, its yield.

Finally, another characterisation of the agricultural capacity of the installation is presented based on the curve of maximum cultivable surface area between collectors as a function of the crop height. Fig. 14 shows this curve for the case study presented. It shows that, of the surface area associated with each tracker (280 m^2, obtained as the product of the distances between trackers d_{EW} and d_{NS}), 207 m^2 (74%) could be cultivated if the crop height did not exceed 1.4 m, while for higher crop heights the surface area available gradually decreases.

In this way, the method presented in this work concludes with the knowledge of the delineation of the available spaces. Specifically, in this work, as mentioned before, the proposed methodology has been applied to the specific case of photovoltaic plant “El Molino”. However, this methodology could be applied to any other photovoltaic plant design and orography, allowing in all cases to determine the maximum cultivable area for its reconversion into an agrivoltaic plant. In addition, although in all the aforementioned cases the maximum height of the cultivable crop is indicated, depending on the specific crop selected, it will also be necessary to consider the limitations imposed, if any, by the dimensions of the machinery required for the corresponding agricultural operations. In that way, the area actually cultivated will depend on the crop finally selected, its specific alignments and distances and the

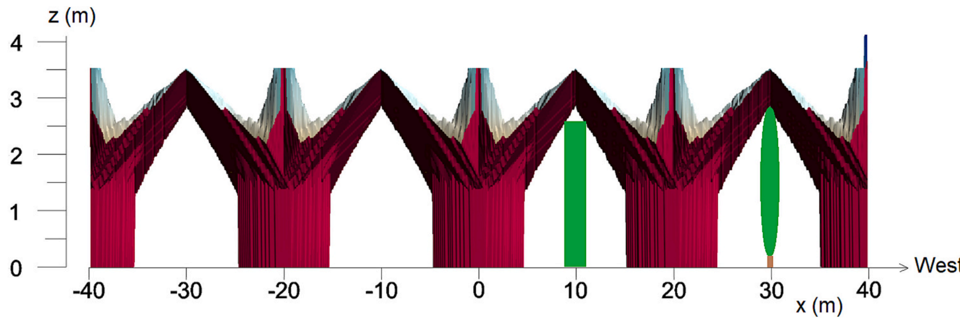

Fig. 10. Frontal view in OXZ plan of the global envelope of the permissible vegetation in the "El Molino" photovoltaic installation.

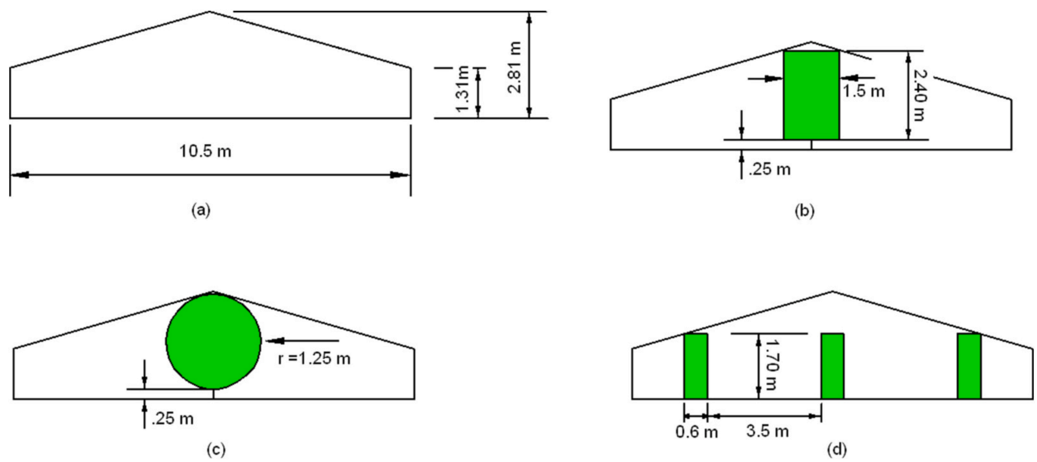

Fig. 11. Cross-sectional profile of open spaces in the N-S direction: (a) dimensions; (b) olive hedge proposal; (c) fruit tree proposal; and (d) vineyard hedge proposal.

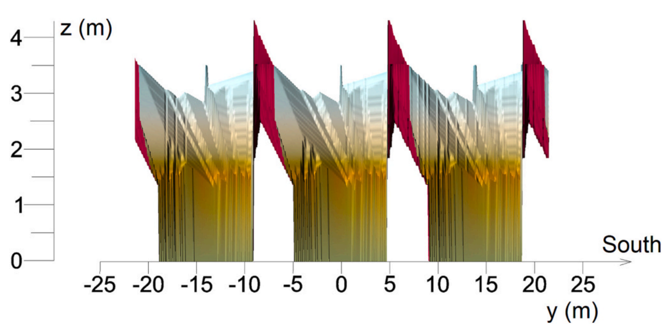

Fig. 12. Side view in the OYZ plane of the overall envelope of permissible vegetation in the "El Molino" photovoltaic installation.

machinery needed for its exploitation, as these will condition the spatial distribution of the crop on the available land.

5. Conclusions

Agrivoltaic production systems involve combining agricultural activities with the production of solar electricity on the same land. This approach offers multiple benefits to agriculture such as maximizing efficiency in land use or reducing conflicts between land uses, among others. Likewise, it presents important benefits to large photovoltaic parks, by providing added agricultural, economic and sustainability value.

In this line, this project has studied the possibility of including agricultural use in photovoltaic plants with dual-axis trackers, with tracking-backtracking based on the azimuthal and elevational axes. The study, focused on the possibility of incorporating crops into this type of plants, has defined a novel methodology that, from the theoretical simulation of the solar astronomy and the spatial geometry of a photovoltaic plant, allows defining and delimiting the space where possible crops would not interfere with the current movement of the collectors. Therefore, the surrounding surface that affects a single collector has been obtained, finding a rational explanation for its shape.

Specifically, the method presented has been applied to "El Molino" plant, located in Córdoba (Spain, latitude 37.75492 N; longitude 5.04548 W), which is a photovoltaic installation with collectors on two-axis solar trackers. The method has allowed the identification of pentagonal arable space between the collectors where different crops could be cultivated. Particularly, along the N-S direction the trapezoidal profile streets available for cultivation have a width of 10.5 m, a minimum height of 1.31 m in the lateral areas and a maximum height of 2.81 m in the middle area. Different proposals for crop occupation in these N-S alignments are suggested both for hedge and for spherical-crowned crops. Likewise, the curve of the percentage of maximum cultivable area as a function of the crop height has been represented, obtaining that for crops with a height under 1.4 m up to 74% of the space between collectors is arable, decreasing this space as the height of the crop increases. Obviously, the actual cultivated land will be lower as this maximum cultivable area may be adapted to the typical and appropriate alignment and geometry for the specific crop selected, as well as to the constraints imposed by the farming operation of the crop. Therefore, the agricultural production of the agricultural plant and its yield will depend on the crop finally selected.

The work carried out represents the first necessary step in the transformation of existing plants to agrivoltaics. Likewise, the progress achieved in this study is very significant, since the natural evolution of the implementation of photovoltaic power plants with dual-axis trackers will require, in the coming years, the search for solutions for their

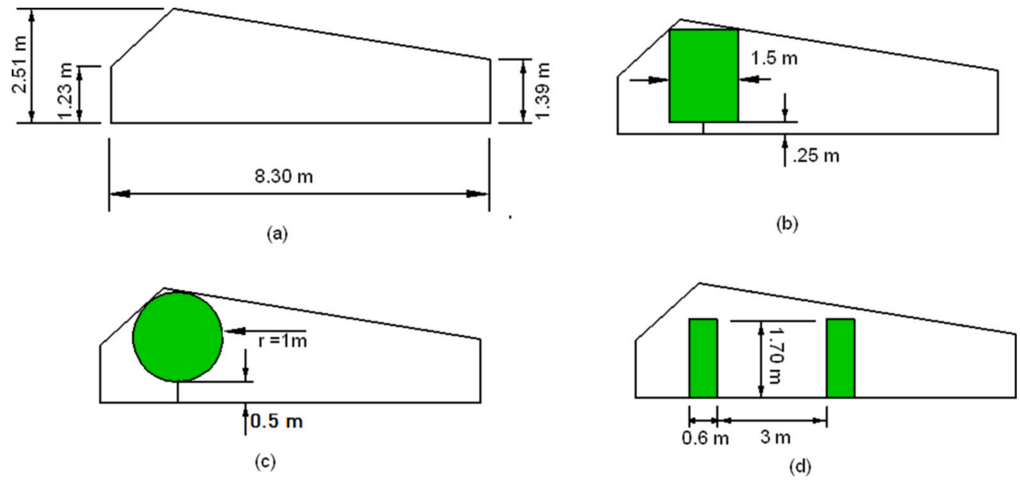

Fig. 13. Cross-sectional profile of clear spaces in the E-W direction. (a) dimensions; (b) olive hedge proposal; (c) proposal for spherical-crowned fruit trees; and (d) vineyard hedge proposal.

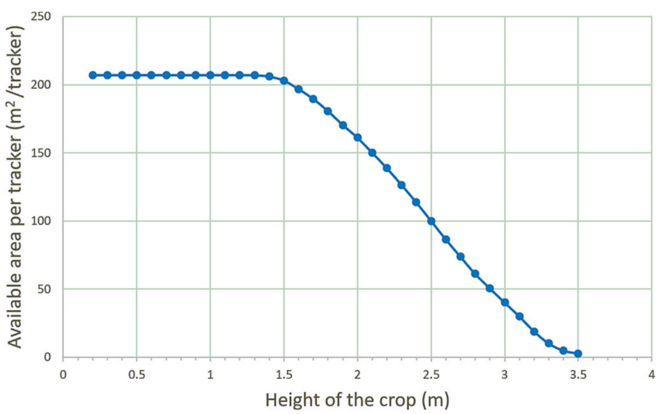

Fig. 14. Area available for cultivation between solar collectors as a function of crop height.

conversion into agrivoltaic installations. However, it is necessary to continue advancing in the study through future work on: (a) available agricultural species and cultivation techniques including all necessary machinery and the planning of operations, (b) radiative uptake in the canopy of the selected crop, including PAR irradiance absorption/ extinction models and spatial homogeneity coefficients, (c) study of Key Performance Indicators (KPI) such as LER (Land Equivalent Ratio), CAPEX (Capital Expenditure), OPEX (Operating Expenses) or LCOE (Levelized Cost of Electricity) (LCOE), (d) influence of the geometry of the crop canopy and solar trackers on the solar irradiance uptake and the agricultural and electrical production, (e) possibility that crops exceed the determined envelope, establishing new patterns of retro-monitoring to avoid shading of crops. Likewise, it is essential to carry out experimental measurement campaigns to corroborate the simulated results and deepen the knowledge of the response of crops to the agrivoltaic conditions described.

CRediT authorship contribution statement

M. Varo-Martínez: Writing – original draft, Supervision, Methodology, Investigation, Formal analysis. **L.M. Fernández-Ahumada:** Writing – review & editing, Visualization, Validation, Resources, Funding acquisition. **J.C. Ramírez-Faz:** Visualization, Validation, Resources, Funding acquisition, Data curation. **R. Ruiz-Jiménez:** Software. **R. López-Luque:** Software, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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