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Characterization of an experimental agrivoltaic installation located in a educational centre for farmers in Cordoba (Spain).

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Abstract. The continuous growth of the world population is causing an increase in the demands for food and energy of the population. Given these circumstances and the negative consequences derived from climate change, it is necessary to evolve towards a more efficient and sustainable agricultural system. In this sense, the agrivoltaic proposes to combine agricultural production and photovoltaic energy production in the same piece of land. Several studies have analysed the behaviour of the agrivoltaic facilities from a theoretical point of view. However, it is necessary to test the viability of this new system in experimental plants. In this work an experimental agrivoltaic plant developed in Córdoba (Spain) is described. The preliminary results of this study show that agrivoltaics can and should play a fundamental role in the energy model of the countries since it promotes the development of renewable energies while improving the economic performance of agricultural land.

Key words. Agrivoltaics, Photovoltaics, Dual use of land, Sustainable agriculture, Climate Change.

1. Introduction

Humanity is currently facing multiple interrelated global challenges, which are largely driven by the increase in the world's population. For example, this increase in population leads to an increase in food and energy needs [1]. It is necessary to find solutions to satisfy both demands simultaneously without compromising the sustainability of the planet. In this context, agriculture, as a fundamental primary activity for the planet (as has become evident during the COVID-19 pandemic), should contribute to mitigate the consequences of the above-mentioned problems. It is therefore necessary to foster a shift in the agricultural production system towards a more energy-efficient and fully sustainable model, so that, instead of being an energy sink, agriculture should tend to become a simultaneous source of food and energy.

In this context, as a solution, agrivoltaics proposes to combine, on the same land, agricultural and renewable energy production, using photovoltaic (PV) technology [2]. Several studies have analysed the behaviour of agrivoltaic facilities [1, 3–11]. The results of these preliminary studies indicate that agrivoltaics can significantly increase the productivity of the land [4, 6, 7, 10, 12]. On the one hand, the shading of PV panels reduces incident solar irradiance and crop temperature, which can benefit some types of crops [1, 7, 9, 11, 13, 14]. On the other hand, diversification of income sources reduces financial risk and improves the profitability of the land [3, 15]. For all these reasons, agrivoltaic systems must be considered essential in a future energy model compatible with climate change and the growing world population's energy and food demands. This situation is especially relevant in Spain, where agriculture is one of the main pillars of the national economy and where the high number of hours of sunshine received throughout the year makes the perspectives for energy sources based on solar resources very favourable.

However, the development of this new paradigm depends to a large extent on scientific advances in characterising its agricultural, energy and economic behaviour. In that sense, for example, although farmers know the behaviour of each plant species in the open field, the situation is different when the crop must grow up under conditions of solar obstruction due to the PV panel shading. Consequently, it is essential to have a deep knowledge on the irradiance received on the different key elements of an agrivoltaic installation (PV panels and crop land) and how the high spatial variability of these solar irradiance maps on the crop may affect agricultural production. Likewise, it is necessary to analyse other variables of interest when characterising the behaviour of this type of facilities such as temperature of the land at different points of the crop, soil moisture, among others. For these reasons, it is essential to collect and analyse experimental data on agrivoltaic plants to analyse the behaviour of different crops under PV panel shading or the technical design of the PV plant to optimise the overall production (agricultural and energy) of the land. In this line, in the present work the main characteristics of an experimental agrivoltaic installation built ex professo are presented.

2. Methodology

The agrivoltaic plant described is located in "Torrealba" Educational Centre, located in Almodóvar del Río (Córdoba, Spain) (37°49'13.3"N 5°00'15.4"W) (Fig. 1). The main objectives of the agrivoltaic plant from a technical point of view are to produce electricity for self-consumption of the educational centre as well as to generate a cultivable space with different solar irradiation conditions due to the PV panel shading (Fig. 1). In this way, by cultivating different species and varieties in the land under the solar collectors, it will be possible to advance in the knowledge of the behaviour of crops under partial shading and different radiative levels. In addition, "Torrealba" Educational Centre pursues, since 1962, the global promotion of the rural and agrarian environment through the training of future farmers. In this sense, from a social perspective, the described agrivoltaic plant will contribute to the future farmers' training as well as the dissemination of the agrivoltaic concept among the rural sector.

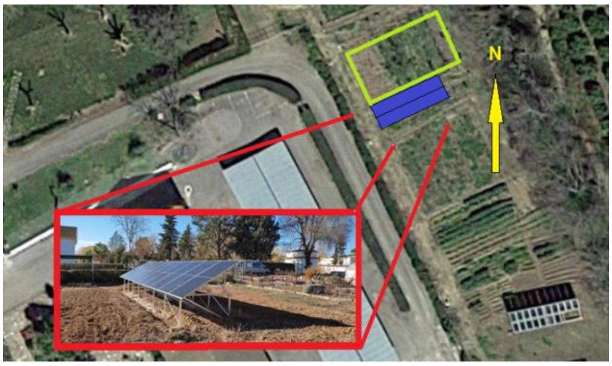


Fig 1. Scheme of the location of the experimental agrivoltaic plant (blue: PV plant; yellow: orchard)

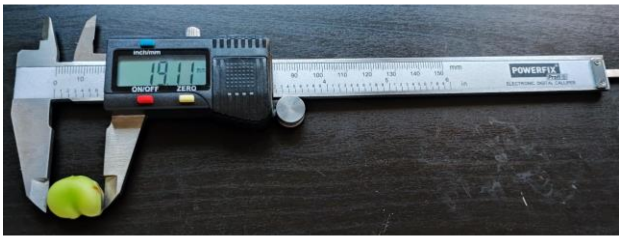
Fig.2. PV installation of the experimental agrivoltaic plant.

As far as the PV part is concerned (Fig. 2), the agrivoltaic plant consists of 10 photovoltaic modules of 535 Wp and a 5 kW single-phase inverter equipped with wireless communications. These panels have been mounted on a support structure 1 m above the ground, made of hot-dip galvanised steel. This height makes it possible to carry out agricultural maintenance work on the crop planted under the structure.

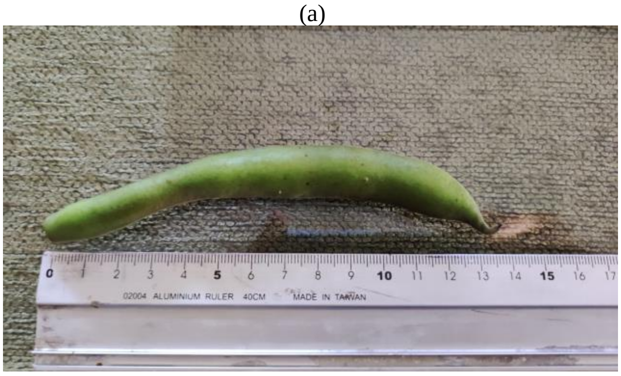
Fig.3. Crop cultivated in the experimental agrivoltaic plant.

From the agricultural point of view, the agrivoltaic facility has been completed with a crop of broad beans *(Vicia faba L. Var. Aguadulce)* planted in lines parallel to the alignment axis of the PV modules (Fig. 3). Specifically, the plants closest to the modules are 0.50 m away from the structure and those furthest away are more than 7 m away. The distance between sowing lines is 70 cm and between sowing points 15 cm. Two seeds have been placed 5-10 cm deep in the ground at each sowing point. In addition, a crop has been planted in front of the PV plant in a configuration identical to the one described above. As this front crop is not shaded by the PV panels, it can be used as a reference for a comparative analysis of the behaviour of the crop on the agricultural plant.

For this crop, which is fully experimental, a phenological study has been designed to quantify the growth and production of the crop (growth curves, flowering, pod set, size and number of pods, weight of grains).



(a)



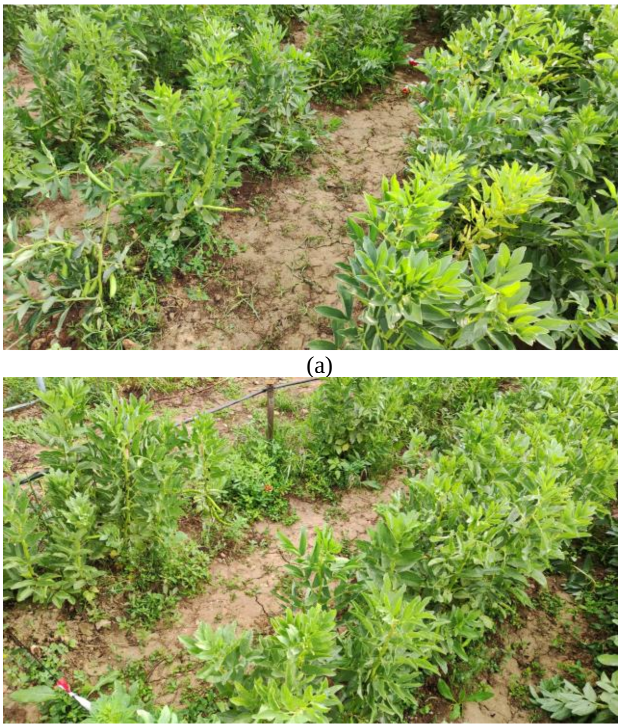
(b)

Fig. 4. Example of experimental measurements developed as part of the phenological study of the crop of the experimental agrivoltaic plant.

As mentioned before, due to the shading of the panels on the crop field, the spatial and temporal variability of the solar irradiance incident on the field is very high. Since radiation levels can affect crop production, the results of the phenological study will be analysed according to the position and degree of shading of each plant. For that purpose, solar irradiance maps on the crop land have been obtained by applying mathematical models based on those proposed by Fernández-Ahumada et al. [16] for estimating incident solar irradiance on surfaces in environments with obstructions. Specifically, these models take into account all the components of solar irradiance (direct, diffuse and reflected) as well as the percentage of the celestial vault free of obstructions that is perceived from each point.

3. Results

In accordance with the above, an experimental pilot agricultural plant has been designed and implemented in "Torrealba" Educational Centre, located in Almodóvar del Río (Córdoba, Spain) (37°49'13.3"N 5°00'15.4"W) in which the agricultural production of a bean crop is combined with the energy production of a 5 kWp PV plant.

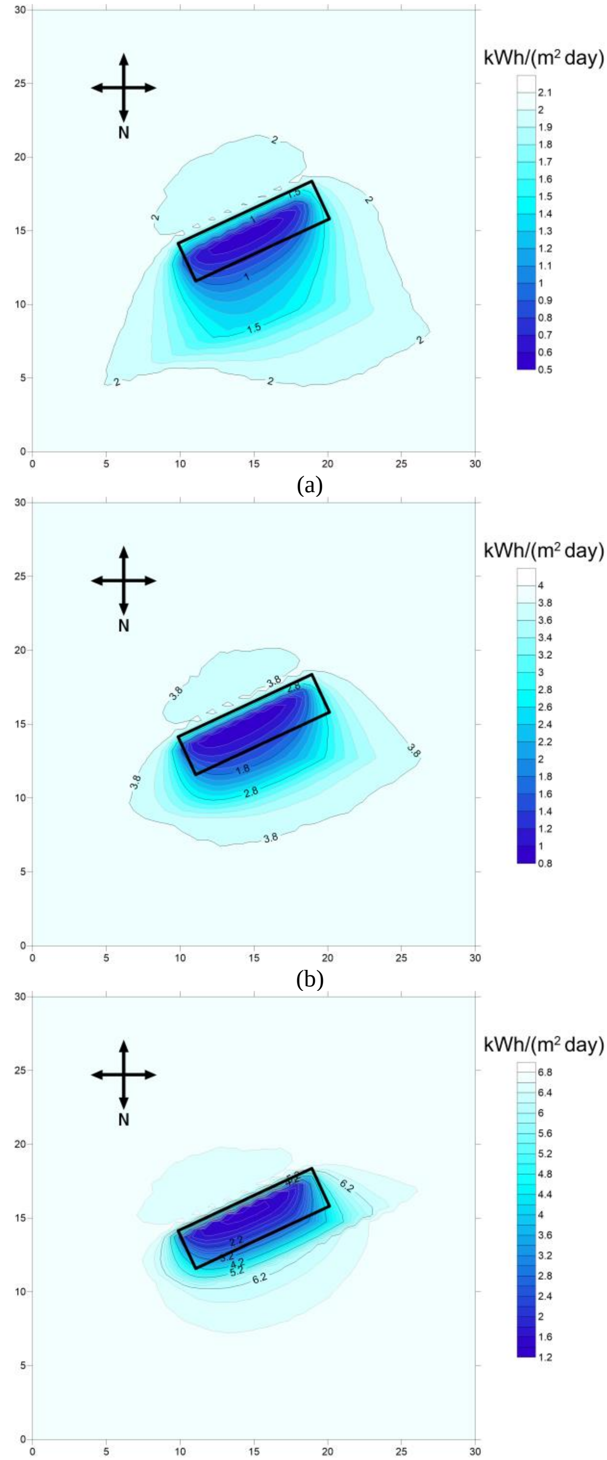

(a)

(b)

Fig. 5. Comparative analysis of the crop (a) behind and (b) in front of (b) the PV facility of the experimental agrivoltaic plant.

As far as crop production is concerned, as shown in Figure 5, the qualitative analysis of the crop behaviour shows that the yield of the broad bean crop is not negatively influenced by the shadows produced by the PV panels on the crop. In fact, the comparative visual inspection of the crop planted behind and in front of the PV plant shows similar results. Likewise, although it has not been possible to complete the phenological study of the crop since at the time of writing this work the harvest time has not been completed, the first results of this phenological study confirm the qualitative results. Thus, the height data of the plants as well as the number of leaves and/or leaflets per plant do not present significant differences between the crop in front of and behind the PV plant.

To relate these results of the crop behaviour with the effect of the PV panel shading, it is necessary to know the solar irradiance maps on the crop land. Fig. 6 shows these solar irradiance maps on the crop obtained by means of the mathematical models based on the methology proposed by Fernández-Ahumada et al. [16]



(a)

(b)

(c)

Fig. 6. Solar radiation (kWh/day) incident on the crop of the experimental agrivoltaic plant on (a) January; (b) March; (c) June

From Fig. 6, Fig. 7 represents the percentage of radiation losses on the crop land due to the PV panel shading with respect to a crop land without shading.

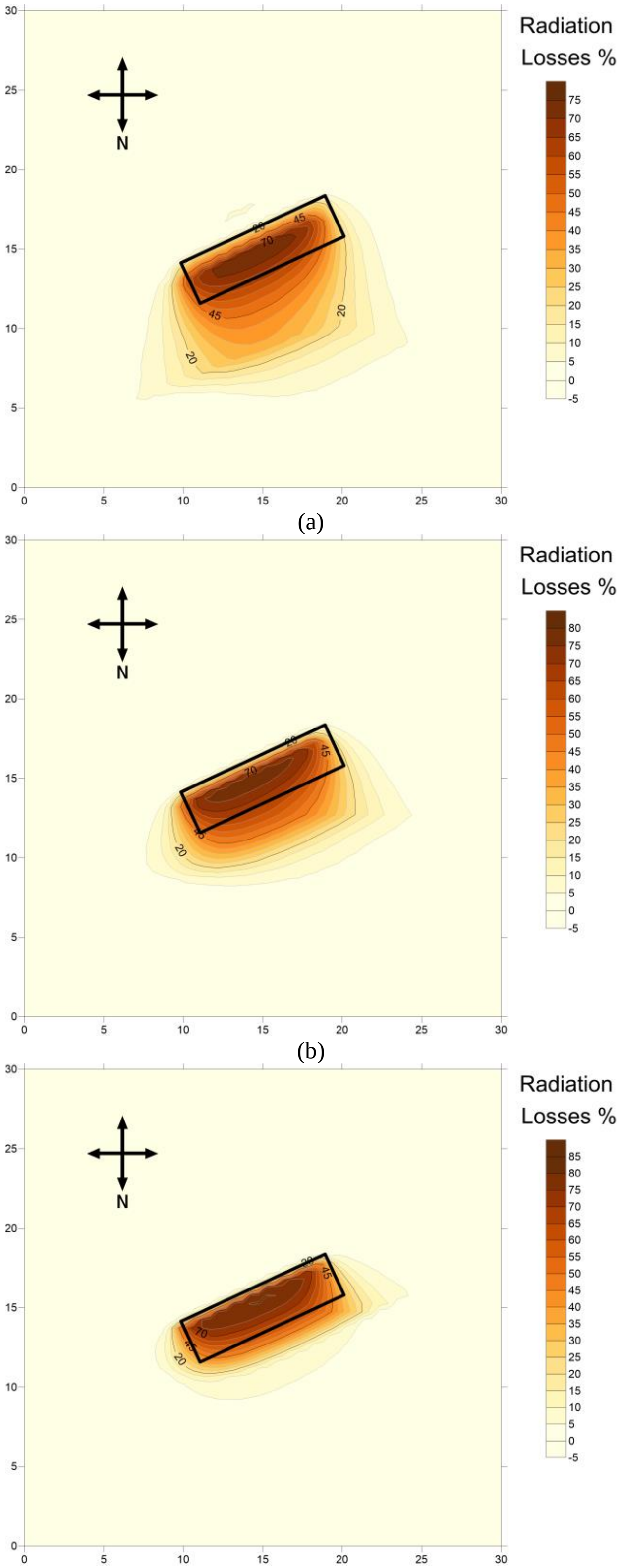


Fig. 7. Percentage of solar radiation losses on the crop of the experimental agrivoltaic plant on (a) January; (b) March; (c) June

Finally, the average monthly PV energy production of the agrivoltaic plant has been simulated (Table I). From this table it can be deduced that the expected average production for the year is 11,980 kWh/year. In addition, the energy production of the PV installation is fully monitored, with the production data available in the cloud (https://eu5.fusionsolar.huawei.com/). Fig. 8 shows the main screen of the application where the energy production is graphically represented (hourly, daily or monthly). It is observed that in the 5 months of operation of the agrivoltaic plant, it has generated 3.35 MWh.

Table I. - Quantitative comparative analysis of daylight levels inside the scale models with and without heliostat illuminators.

Month	Average monthly PV production (kWh/month)
January	649.4
February	825.5
March	1020.4
April	1072.8
May	1137.7
June	1280.9
July	1378.6
August	1371.3
September	1168.4
October	884.8
November	664.7
December	532.9

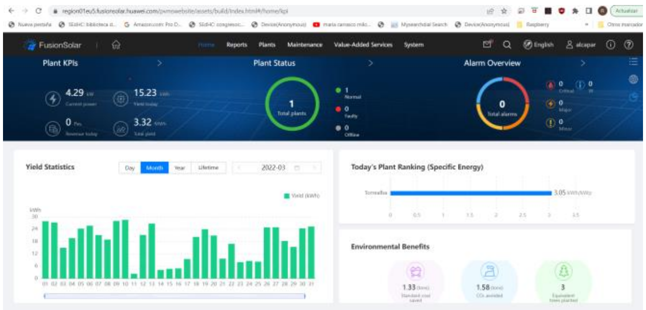


Fig. 8. Monitoring system of the energy production of the experimental agrivoltaic plant

4. Conclusion

This paper presents the characterization of an experimental agrivoltaic plant developed at the "Torrealba" Educational Centre (Almodóvar del Río, Córdoba, Spain). This agrivoltaic plant is made up of a 5 kWp PV plant mounted on an elevated structure 1m above the ground to allow the necessary agricultural work to maintain the crop. A phenological study has been designed to analyse the behaviour of the crop and its agricultural production. Likewise, the energy production of the PV plant and the behaviour of the solar irradiance on the crop, due to the shadows of the PV panels, have been simulated and the maps of solar irradiance on the crop have been obtained. The combined study of these results will allow to characterize the behaviour of agrivoltaic plants and conclusions could be drawn about the economic profitability of this type of plant, as well as the design characteristics of the PV plant and the most optimal type of crop for this type of installation. In this way, agrivoltaics is presented as a viable solution in the search for a new, more efficient agricultural system that allows to met the growing demands for energy and food in a sustainable way without compromising the future of the environment.

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