



# Floating photovoltaics systems on water irrigation ponds: Technical potential and multi-benefits analysis

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## ABSTRACT

Floating photovoltaic systems (FPV) can be a more sustainable alternative for the energy transition than ground-mounted photovoltaic systems, as they avoid occupying useable land and the power generation is more distributed. This paper presents the first study that calculates the FPV technical potential at the province/municipality level, focusing on water irrigation ponds, which it is a novelty in the literature that usually focuses on large water infrastructures in a national approach. In the province of Jaén (Spain), more than 3000 ponds dedicated to agricultural irrigation have been identified and their surface area and location was obtained. The results, calculated for each pond, reveal that, in a conservative scenario, in which only 25% of their surface area is covered, a minimum of 490 MWp can be installed, which can provide 251% of the province agricultural electricity consumption and 27% of the total electricity needs. This analysis has also been performed at the municipal level, where all possible FPV plants have been aggregated and compared with consumption that would be covered at this scale. Furthermore, this technology brings additional benefits, as it avoids the occupation of 12 km<sup>2</sup> of useable land, 8.8·10<sup>6</sup> m<sup>3</sup>/year of water evaporated, while creating more than 7000 jobs.

## 1. Introduction

Despite the progress made in the penetration of renewable energy (RE) sources in most parts of the world, it is still not fast enough to achieve the international climate mitigation targets [1]. Furthermore, in the energy planning procedures it is becoming paramount to include aspects beyond the techno-economic ones [2], in order to implement policies that not only reduce greenhouse gas (GHG) emission, but also that avoid other environmental problems and social conflicts whilst generating socio-economic benefits. In this regard, solar photovoltaic (PV) is one of the most promising RE technologies due to its ubiquity and sustainability [3]. In fact, solar PV is expected to be the leading RE technology by 2050 [4] and to create many jobs during a climate compliant global transition across all energy sectors [5]. However, concerns about the environmental impacts and land use conflicts of large-scale ground-mounted PV plants, specifically in Spain [6], are

causing uncertainty and some opposition in the implementation of this technology.

As an alternative to these concerns, floating PV (FPV) systems are an emerging application which has doubled its installed capacity every year [7]. In fact, FPV systems are cost-competitive compared to ground-mounted solar PV farms due the absence of land acquisition costs. It also provides some additional and unique features, including the reduction of water evaporation of the irrigation canals [8], reservoirs or ponds where it is installed, together with a mitigation of algae growth [9]. In addition, some authors claim a higher efficiency of electricity generation compared to common PV systems because of the cooling effects of water and, finally it prevents land-use conflicts [10]. Moreover, FPV projects could mitigate climate change impacts on water body temperature and stratification [11], imply water-food-energy nexus synergies [12], and they are gaining social support [13].

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### 1.1. Literature review

The analysis of FPV applications are an emerging topic in the scientific literature. Fig. 1 shows the articles published throughout the time which are indexed in the two main scientific databases, i.e. Scopus and WoS. The search strategy has been set by looking for “floating photovoltaic” or “floating PV” in title, abstract and keywords of review and research articles.

As can be deduced from this figure, 62% of the manuscripts were published from 2020 onwards (until June 12th, 2022). However, only 18 of the 195 papers are focused on evaluating the FPV technical potential at different territorial scales. This indicates that the technical potential estimation of the FPV systems is a less discussed topic in this field.

Table 1 summarised the research articles that evaluate the FPV technical potential at different territorial scales and water bodies' types. It also includes additional reported indicators to the technical potential.

It is highlighted that two thirds of these manuscripts have been applied at national scale (with regional/state results) and only two studies were applied at sub-national scale (regional results, both applied to Brazil). To the authors' knowledge, up to the date of submission, there are no applied studies focused on a more local scale (for instance, with province/municipal results).

Reservoirs for hydropower generation have been the most analyzed water body (included in 89% of the works) and irrigation ponds (included in 28% of the studies) have only been evaluated simultaneously to other artificial water bodies, but not independently.

Beyond the techno-economic indicators, the additional reported factors have been focused on GHG emission avoidance and water evaporation reduction, but these aspects are not included in all articles. However, to the authors' knowledge, no manuscript has been published on job creation related to FPV projects.

### 1.2. Aim, novelty and contribution of this research work

Considering that the technical potential estimation of FPV systems has been less discussed in the scientific literature, especially for a municipal scale and for irrigation ponds independently, the main objective of this work is the calculation of the FPV potential to be installed solely on water irrigation ponds located in the province of Jaén (Andalusía, Spain).

Another side objective of this research is the estimation of the multi-benefits, beyond the techno-economic ones, that this technology may also provide. This analysis can be useful for energy planning processes and the implementation of the PV technology in a more sustainable manner.

The province of Jaén has been used as case study because it is a territory with unexploited good solar resource, a pronounced unbalance between its electricity production and consumption, and a significant

agriculture sector based on olive crops that request water irrigation to maintain its productivity.

The multi-benefits analysis included are the estimation of the avoided land to be occupied for the same capacity and electricity generation of the FPV technical potential calculation, and its level of matching the electricity demand of different sectors at the municipal and province level.

Furthermore, the avoided annual CO<sub>2</sub> emissions and the estimation of annual water evaporation reductions, together with the evaluation of the potential number of jobs creation in the implementation and operation stages are also other benefits considered in this study.

Therefore, the novelty of this research can be summarised as follows:

- i) It is the first study that calculates the FPV technical potential at province/municipal level and focused only on water irrigation ponds.
- ii) It is the first work to report on jobs creation from FPV technical potential
- iii) It is the first time that the FPV technical potential is compared with the electricity demand from different sectors (agriculture, residential, etc.) at municipal level.

The main contribution of this work to the existing literature is a replicable approach that calculates the FPV potential at a local level and estimates multi-benefits beyond the techno-economic ones, which expands the understanding on how to accelerate the energy transition needed for achieving the climate goals in a more sustainable manner that, at the same time, can gain social support.

### 1.3. Structure of the paper

This paper is structured as follows. Section 2 provides a contextualization of the study case location. Section 3 describes the methodological approach for calculating the FPV technical potential and its multi-benefits. The results are presented in Section 4, whereas the discussion and limitations of this work is detailed in Section 5. Finally, in Section 6, conclusions and future works are exposed.

## 2. Contextualization of the study case location

The context of the current study starts with a description of the energy situation in the province of Jaén, which will serve as a comparison with the electricity generation capacity of the proposed FPV systems.

Additionally, the reason for the existence of the irrigation ponds in the province is commented, where in one of them, the first FPV system existing in the province has been installed. This system was selected as a reference for this study.

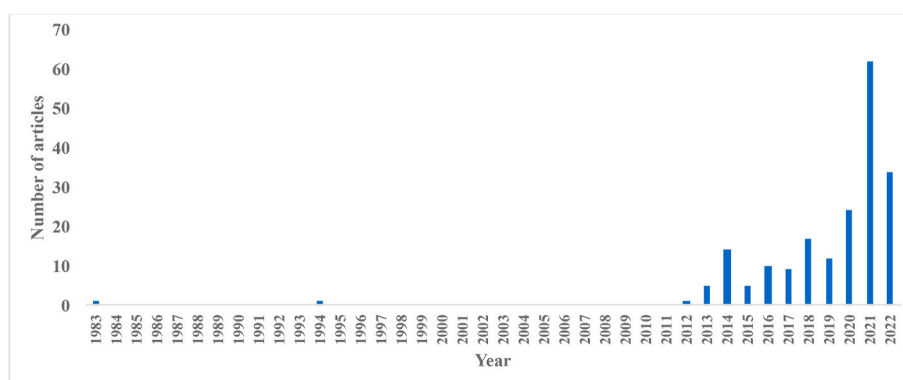


Fig. 1. Number of FPV scientific articles indexed in SCOPUS and WoS databases.

**Table 1**  
Research articles that evaluate FPV technical potential at different territorial scales.

Reference	Scale	Natural water body (lakes)	Artificial water body				Additional reported indicators	
			Reservoir (power generation)	Reservoir (water supply)	Irrigation pond	Industrial pond	CO <sub>2</sub> emission reduction	Evaporation reduction
Perez et al. [14]	National	x	x					x
Farfan and Breyer [15]	Global		x					x
Tina et al. [16]	Global	x	x	x	x	x		
Kim et al. [3]	National	x	x	x			x	
Château et al. [17]	National					x		
Spencer et al. [18]	National		x	x	x			x
Campos et al. [19]	Sub-national			x				x
Zubair et al. [20]	National	x	x	x				
Stubiener et al. [21]	National		x					
Micheli [22]	National		x	x	x			
Muhammad et al. [23]	National	x	x	x	x			
Quaranta et al. [24]	Continental		x					
Gonzalez et al. [25]	Continental		x					x
Sulaeman et al. [26]	National		x					
Ravichandran et al. [27]	National		x				x	x
Moraes et al. [28]	Sub-national		x				x	x
López et al. [29]	National	x	x	x			x	
Campos et al. [10]	National		x	x	x	x		

### 2.1. Energy situation in the province of Jaén

The province of Jaén is located in the South of Spain and belongs to the region of Andalusia. It occupies an area of 13,496 km<sup>2</sup> and it is divided into 97 municipalities. This province is characterized for being an eminently agricultural region, where the olive grove is the main crop.

The final electricity consumption in Andalusia amounted to 2912.0 ktoe in 2020. For that year, in the province of Jaén, consumption was 229.3 ktoe, representing 7.86% of the Andalusian total [30].

Disaggregating this consumption according to the different economic sectors, the highest electricity consumption in Jaén was achieved by the residential sector with 93.1 ktoe (41%), followed by the industrial sector with 55.9 ktoe (21.02%) and the services sector with 55.1 ktoe (21%). On the other hand, the primary sector and transportation were the activities that consumed the least electricity, with 24.8 ktoe (10.5%) and 0.5 ktoe respectively [30]. Table 2 shows the consumption information by sector.

In Jaén, in recent years, there has been a decrease in the final provincial electricity consumption, from 274.2 ktoe in 2005, to 229.3 ktoe recorded in 2020 [30]. The commitment to energy efficiency and the greater share of renewable energies in the consumption and generation structure of the province explain this trend. However, if the consumption data are compared with the total gross electricity production in Jaén, which for 2020 was 1723.8 GWh (148.15 ktoe), a negative electricity balance between production and consumption of 81.1 ktoe is

**Table 2**  
Electricity consumption by sectors in 2020 in Andalusía and Jaén.

	ANDALUSIA (GWh)	JAEN PROVINCE (GWh)
AGRICULTURE	1517.23	289.76
INDUSTRY	8391.19	669.46
BUSINESS – SERVICES	6081.36	361.42
RESIDENTIAL	13,198.92	1079.72
ADMINISTRATION-PUBLIC SERVICES	3718.21	262.55
OTHER	337.40	21.83
TOTAL	<b>33,244.31</b>	<b>2684.73</b>

observed. It could be stated that Jaén is energetically dependent on the neighboring provinces.

Considering the distributed nature of photovoltaic technology, as well as the dispersion of irrigation ponds in the province where the floating potential study will be carried out, this consumption has been disaggregated to each of the 97 municipalities in the province. Fig. 2 shows the map of the province of Jaén where the total consumption of each municipality is shown, highlighting the relevance that the electricity consumption of the agricultural sector for each municipality has in the total consumption of each location.

Regarding the electricity generation, in 2021 Jaén had 598.46 MW of installed capacity in its territory, of which 422.96 MW belongs to renewable electricity generation facilities, which accounted for 4.73% of the Andalusian total, and whose gross electricity production was 605.2 GWh [31] (Table 3). Throughout its territory there is a wind farm with an installed capacity of 15.2 MW, three biomass power plants (16 MW, 15 MW and 6 MW respectively) and more than 50 solar PV plants with individual power generally below 10 MW, and up to the date (June 2022) the largest being 11.8 MW. Despite this installed capacity, the renewable electricity generated in Jaén only accounts for 28.9% of the total final energy consumption of the province, estimated for 2021 at 229.3 ktoe [31]. In addition, there are no fossil fuel or pumped hydroelectric generation facilities in the province, so the electricity generation system is based entirely on RE systems and cogeneration plants [31]. Most of the electrical consumption of Jaén has to be imported from the surrounding provinces.

### 2.2. Irrigation ponds in the province of Jaén

The main driver of agricultural modernization processes has been the intensive use of available resources [32]. In Andalusia, the conditioning factors of the Mediterranean climate, characterized by irregular and scarce rainfall and high transpiration, make water a limited resource that is disputed between domestic use and the expansion of irrigation, which in the specific case of this province has experienced in recent decades [33].

Since the second half of the 20th century, continuous political interventions were implemented in the province of Jaén aimed at the

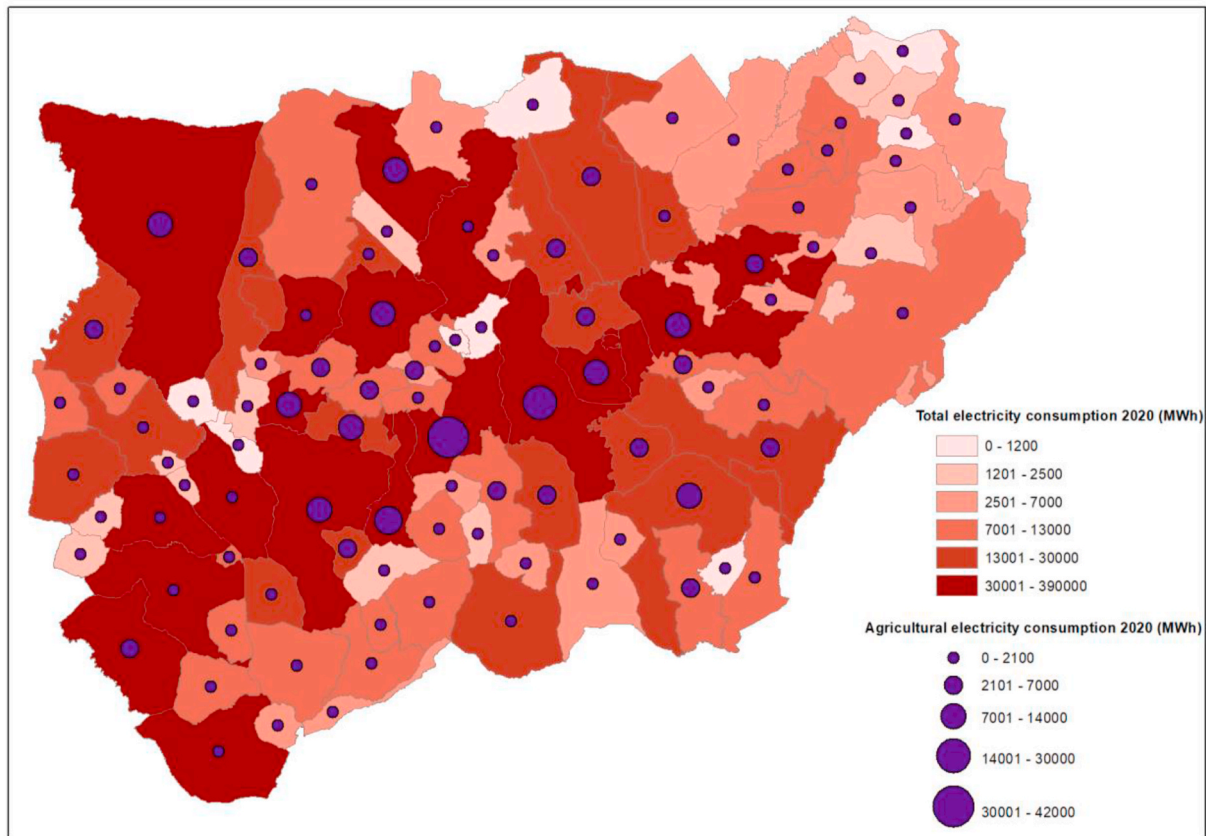


Fig. 2. Total and agricultural electricity consumption by municipality in the province of Jaén.

**Table 3**  
Installed capacity and renewable electricity generation in the province of Jaén by 2021.

	BIOMASS	HYDRAULIC	SOLAR PV	WIND	TOTAL
Power Installed (MW)	37.0	212.2	157.44	15.18	422.96
Electricity Generated (GWh)	239.2	178.0	161.8	26.3	605.2

expansion of the irrigated area, materialized in the construction of an extensive network of reservoirs along the Guadalquivir River and its main branches [34]. However, after Spain’s entry into the European Union and the linking of agricultural aid to the Common Agricultural Policy (CAP), a framework of productivity and intensification driven by these policies is generated in Jaén [34]. In this new context, the existing hydraulic infrastructures for irrigation turned insufficient, giving rise to



Fig. 3. Example of a typical water irrigation pond existing in Jaén.

a proliferation of water ponds in private farms, similar to the one shown in Fig. 3, that aim to optimize the use of water for irrigation and guarantee the water supply to their crops in summer or drought seasons [32].

In Andalusia, the largest ponds are located in the agricultural areas of the Guadalquivir valley, among which the province of Jaén stands out, together with Córdoba and Seville, which is explained by the large extensions of the properties together with the shared use of some ponds by several owners [32].

Fig. 4 shows the area that these ponds occupy for each of the municipalities existing in the province. This value will be very useful for the FPV potential calculation to be installed in each location.

### 3. Methodology

In order to achieve the objectives proposed in this research, that is, the identification of the technical power and energy potential of floating PV systems in a certain region, together with the quantification of additional benefits (social, economic or environmental), the following methodology is proposed, which, it is graphically represented in Fig. 5.

The first step is to define the type and characteristics of the water infrastructure for the installation of these FPV systems. In this manuscript, to avoid any conflict with the aquatic biodiversity, only artificial water infrastructures are analyzed. Furthermore, unlike similar studies carried out in Spain [29], this research has excluded dams and reservoirs. It has only focused on water accumulation volumes oriented to agricultural irrigation activities, since the installation of FPV systems in these locations does not conflict with other uses (recreational, fishing) or with water quality problems that can be found in large reservoirs. Moreover, in the specific case of Spain, irrigation ponds are not affected by the percentage limit of surface coverage that may impose the future national legislation (currently in the public consultation phase), which establishes different coverage limits up to 20% of the water surface)

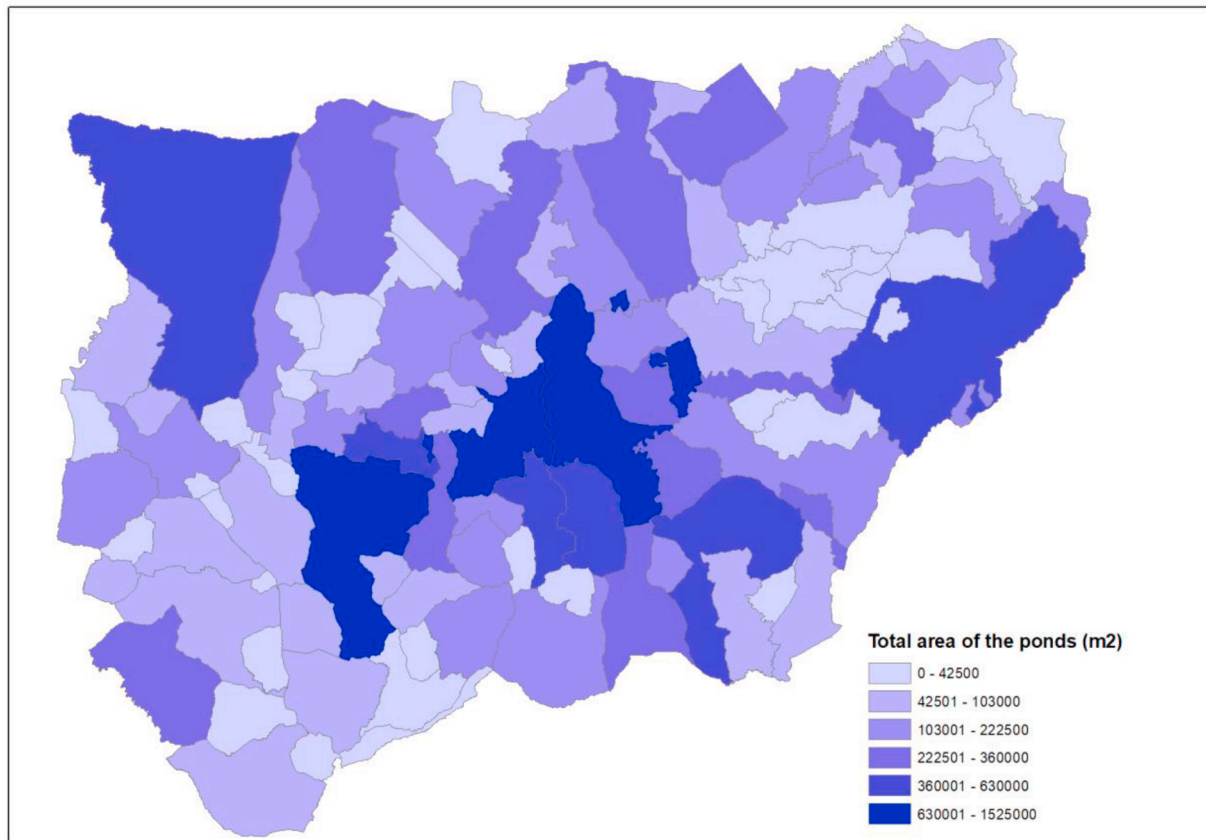


Fig. 4. Water Irrigation Pond area identified for each municipality in Jaén.

depending on the trophic state of the reservoir [35].

Furthermore, an additional screening filter is applied, as other (non-water) liquid accumulation infrastructures, which are common in agricultural and livestock activities, were also excluded. For example, ponds dedicated to the toxic liquid waste resulting from pressing the olives for oil production, as well as ponds dedicated to livestock manure, have been ignored.

The next step in the methodology consist of identifying, within a specific region, those water infrastructures that meet the previous requirements. For this purpose, their location coordinates are obtained, as well as the water surface occupied by these ponds (in the most favourable case, that is, when they are full). Specifically for the region analyzed (the province of Jaén), all the water infrastructures dedicated to olive tree cultivation have been identified. The cartographic data provided by the Multiterritorial Information System [36] were used for this task.

The third step consists of processing the list of registered water infrastructures in order to discard mainly those reservoirs that do not meet the requirements of the first step. Subsequently, based on their location coordinates, these infrastructures have been grouped according to the municipalities to which they belong. Subsequently, the global central point (centroid) of all the ponds in a given municipality is calculated, to be used as reference coordinates for the meteorological data. The geospatial processing software ArcMap was used for this task.

The fourth step in the methodology, prior to the calculation of the photovoltaic energy, consists of selecting the meteorological data from these reference centroids. It is recommended that the data correspond to the typical meteorological year (TMY), which consists of recording several meteorological measurements at hourly intervals over a period of several years to build a picture of the local climate, thus reducing the uncertainty that could be caused by using weather data from a specific year. Among the available meteorological data sources, the PVGIS tool

(version 5.2), which provides (open access) solar radiation databases, was considered. In this research, the PVGIS-SARAH2 database was used, whose data are satellite-based and covers a time period from 2005 to 2020, was considered [37].

The simulation of the electrical performance also known as final energy yield, that is, the energy generated per unit of installed PV power ( $Y_F$ , kWh/kWp) that a floating PV system would have at the identified centroid locations, is the fifth step of this methodology. In this study, the characteristics and configuration of the FPV demo system already installed in Jaen (see Fig. 6) were taken as reference, therefore a tilt angle of  $5^\circ$  was selected for the simulation.

In addition, it is useful to estimate the equivalent agricultural area needed to produce the same energy as the floating system, but installing the PV plant on the ground instead. Therefore, the electrical performance of a PV installation with an optimised inclination for each of the calculated centroids was also simulated. The tilt angle of these systems matches the latitude of the centroid locations.

This procedure was performed with the dedicated photovoltaic simulation software System Advisor Model (SAM) developed by the NREL research centre [18]. In a first approximation, the global losses of the PV system set by default by the software were chosen, because although some authors mention possible energy gains due to the cooling effect of the water, these conclusions are not yet sufficiently corroborated and in some cases, depending on the type of floater used, these energy improvements are not so high [38]. Furthermore, the possible energy boost could also be counteracted by the effect of dirt, especially from bird drops, as the isolation of the location of these irrigation ponds is often more prone to the accumulation of this type of dirt.

Subsequently (step 6), the energy generated per unit area of water or land ( $E_A$ , kWh/m<sup>2</sup>) of both the floating PV and the optimally tilted system at the centroid location was estimated. For this calculation, the PV power per unit area ( $K_{pV_A}$ , kWp/m<sup>2</sup>) of a standard FPV and of a

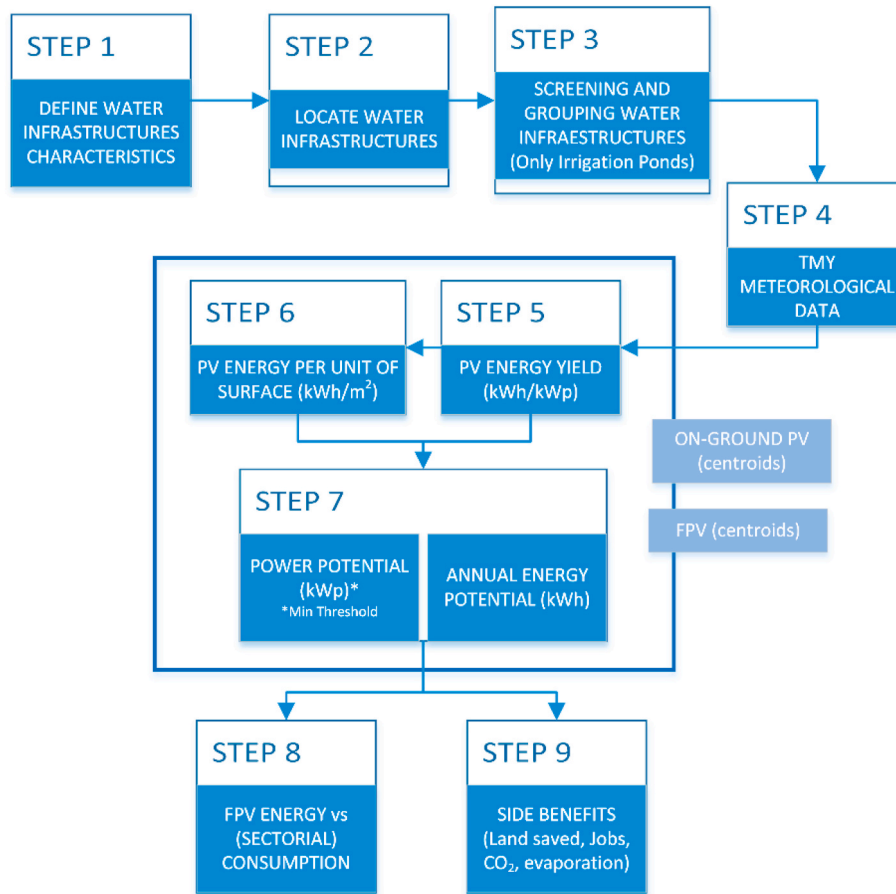


Fig. 5. Graphical representation of the methodology.

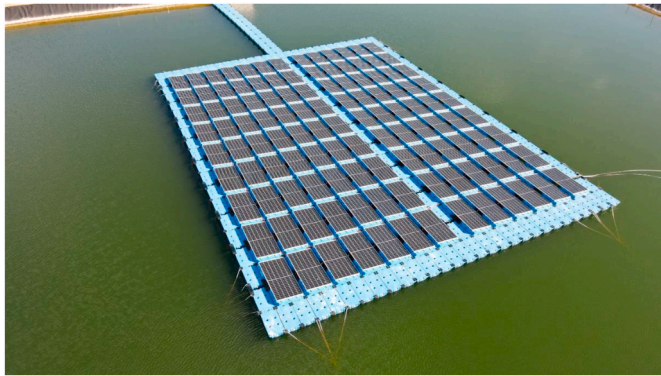


Fig. 6. First FPV plant installed in the province of Jaen by Desarrollos Tecnológicos Intelec S.L.

ground-based system is provided.

Therefore, considering the annual energy yield ( $Y_F$ ) simulated for each system, the energy per unit area can then be calculated according to the following formula:

$$E_A (kWh / m^2) = K_{pvA} (kWp / m^2) \cdot Y_F (kWh / kWp) \quad (1)$$

To estimate the constant  $K_{pvA}$  value, the peak PV power and the water surface covered by the floating PV system already installed in Jaén (see Fig. 6) has been used. This FPV plant has a peak power of 52.7 kWp and it occupies a water surface of 401 m<sup>2</sup>, therefore, the  $K_{pvA}$  value used in this study is 0.131 kWp/m<sup>2</sup>.

On the other hand, the constant  $K_{pvA}$  value to be considered for

ground-mounted PV plants was obtained from data of real installations available in the repertoire of the Andalusian Statistic and Cartographic Institute (Instituto de Estadística y Cartografía de Andalucía): Spatial Reference Data of Andalusia (Datos Espaciales de Referencia de Andalucía), provided by the Regional Andalusian Government [39]. Considering the individual surface of all the existing solar photovoltaic plants (fixed ground-mounted) located in the province of Jaén, and their corresponding peak power value, an average  $K_{pvA}$  value of 0.388 MWp/ha was considered. Similarly to the FPV systems, the energy per unit area of the ground-mounted PV plants can then be calculated according to equation (1).

For each of the identified and filtered irrigation ponds, three analysis scenarios were proposed in relation to the water surface ( $S_w$ , m<sup>2</sup>) than can be covered by the floating. Starting with the most optimistic case, it has been considered that 100% of the water pond area is covered by this type of FPV systems which, although not realistic, is indicative of the maximum eligible power to be installed. Subsequently, scenarios with a water coverage percentage ( $C_w$ , %) of 50% and 25% were also considered. The decision to set the latter value corresponds to the surface area available at the minimum level of the pond under study (Figs. 3 and 6), that is, in the absence of water. In this demonstration installation, the floats are designed to rest on the bottom of the pond without damaging its waterproofing layer.

Considering these water surface occupancy scenarios, the surface of each pond and the photovoltaic power per unit of surface ( $K_{pvA}$ ), the next step in the methodology was to obtain the photovoltaic power potential ( $P_{FPV}$ , kWp) and the annual energy production ( $E_{FPV}$ , kWh) of each of the 3177 ponds registered in Jaén (see equations (2) and (3)).

$$P_{FPV} (kWp) = K_{pvA} (kWp / m^2) \cdot \frac{C_w(\%)}{100} \cdot S_w (m^2) \quad (2)$$

$$E_{FPV}(kWh) = E_A(kWh/m^2) \cdot \frac{C_w(\%)}{100} \cdot S_w(m^2) = P_{FPV}(kWp) \cdot Y_F(kWh/kWp) \quad (3)$$

According to the methodology, there is no minimum FPV power system that could be installed potentially. This approach may distort the results obtained, since there could be numerous very small irrigation ponds that could not be implemented in practice due to a lack of technical or economic feasibility. For this reason, a filter has been applied that introduces a minimum photovoltaic power to be installed in the localized ponds. This filter has been set firstly at 10 kW and in a second approximation at 50 kW, to resemble the size of the plant taken as a reference (Fig. 6).

The result of this methodology enables us to compare the potential floating photovoltaic electrical generation with the electricity consumption by sectors in the province of Jaén (Table 2). Besides the provincial approach, this comparison has also been applied at the municipal level where irrigation ponds exist (94 out of 97), therefore the percentage of municipal electricity consumption which could be provided by FPV systems located in these municipalities was also calculated.

Complementary analysis were carried out to assess the impact of the results on additional benefits.

Firstly, the area for olive crops that is prevented from being occupied by ground-mounted photovoltaic plants was studied. For this purpose, two analysis strategies were proposed. On the one hand, the surface area that a fixed ground-mounted plant would need to occupy (with its optimum inclination) to achieve the same power as the floating systems obtained is considered. The other scenario consists of determining the area that the ground-mounted systems would need to produce the same amount of energy as that generated by the floating installations.

Subsequently, additional positive side effects were calculated. In this manuscript, these benefits focused on the job creation rates, CO<sub>2</sub> emissions avoidance and the reduction of water evaporation due to the surface covered by the PV modules and floaters.

The estimation of the number of direct jobs created in the construction and installation (C&I) and in the operation and maintenance (O&M) phases is based on previous research. The following employment factors were used: 13 jobs/MWp and 0.7 jobs/MWp for C&I and O&M, respectively [5].

Regarding CO<sub>2</sub> emissions reduction, it was considered between 0.364 and 0.826 ktCO<sub>2</sub>/GWh, which is the range of CO<sub>2</sub> emission factor that depends on the specific fossil fuel-based electricity generation technology [40].

Finally, to estimate the reduction of the water evaporation, as a consequence of covering the irrigation pond with FPV systems, a factor based on the annual values reported by Santafé et al. [41] was used: 16, 667 m<sup>3</sup>/MWp.

### 3.1. Methodology limitations and uncertainties

The largest uncertainty in the PV energy estimations comes from the solar radiation data. Satellite-based meteorological data have been used in this study. Although local meteorological measurements might presumably be preferable, data covering the spread of the numerous ponds identified in this study are not available, so the error that can be made using environmental data for ponds located far from these weather stations may be larger than using satellite data.

Some authors report a typical normalized root mean square errors for satellite-based irradiation of between 2 and 6% for yearly irradiation values [42]. However, other studies mention that data sets generated from long time series perform better than data generated from station measurements [43], so the results of this research may be even improved.

The annual radiation variability is also another uncertainty of this study that may limit the results. Some authors estimate a 3.9% inter-annual climate variability [44]. In this regards, as mentioned in the

methodology, the use of TMY reduces the uncertainty when compared to weather data for a specific year.

Another uncertainty source comes from the simulation of the energy generated. There are published reports applied to the SAM software that indicate a bias error of ±3% when compare to measured data [45,46]. Nevertheless, in this manuscript the losses were set as the software's default, but according to some authors, the energy yield improvement of FPV systems due to the cooling effect of the water could be between 5 and 10% [47], therefore, the above uncertainty may be easily overcome.

One of the limitations in the simulation comes from the ponds morphology and the water level variations. When the ponds are much lower than their capacity, but the system was designed to cover 100% of the water surface, although the FPV system is prepared to lay down on the pond's walls, mismatch losses may appear among the PV arrays. Furthermore, if the FPVs do not cover the entire water surface, when the pond is empty, the walls can cast shadow on the FPV generator, therefore, energy losses are produced. This limitation should be approach in future works.

## 4. Results

According to the sort of water infrastructures filter imposed in the methodology section, 3177 water irrigation ponds have been identified only in the province of Jaén for the installation of floating PV systems, with a total surface of 16 km<sup>2</sup>.

For each irrigation pond located, the potential FPV power to be installed has been calculated according to the coverage scenarios described previously, and subsequently, the energy generated has been obtained. In addition, the land to avoid occupying, which can be useful for other purposes, has also been calculated.

### 4.1. Floating photovoltaic power potential and energy production

In order to avoid a distortion in the results shown in Table 4, a minimum power threshold for the FPV plant was considered.

In the idealistic case, where 100% of the water surface is covered and no minimum power is required for the implementation of an individual FPV system, 2.1 GWp could potentially be installed in this region only using existing irrigation ponds. On the other hand, the most conservative scenario corresponds to the use of only 25% of the total available area in each irrigation pond, and photovoltaic systems with peak power greater than 50 kWp. In this scenario, up to 490 MWp could be installed, which, assuming a PV generator/inverter ratio of 1.2, would mean 408 MW of nominal (inverter) power. This figure represents 2.6 times the current photovoltaic capacity existing in the province of Jaén, and approximately matches the renewable energy capacity installed in the province until 2020.

The most technically feasible and realistic scenario corresponds to FPV systems above 50 kWp and up to 50% of the water surface area of each pond covered. In this case, FPV systems totalling one GWp could be potentially installed, which represents 5.4 times the existing PV capacity in the province.

These results depends not only on the percentage of water surface covered, but also on the size of the FPV system. Fig. 7 shows the distribution of FPV power system size as a function of percentage of surface covered. The homogeneity in the distribution of systems shifts towards lower power systems, as this area is reduced. In any case, most of the

**Table 4**  
Peak Power Floating PV potential in the province of Jaen at irrigation ponds.

FPV POWER (MWp)	100% Surface	50% Surface	25% Surface
no power	2113.99	1057.00	528.50
FPV threshold			
FPV > 10 kWp	2113.93	1056.03	525.90
FPV > 50 kWp	2097.09	<b>1025.34</b>	490.51

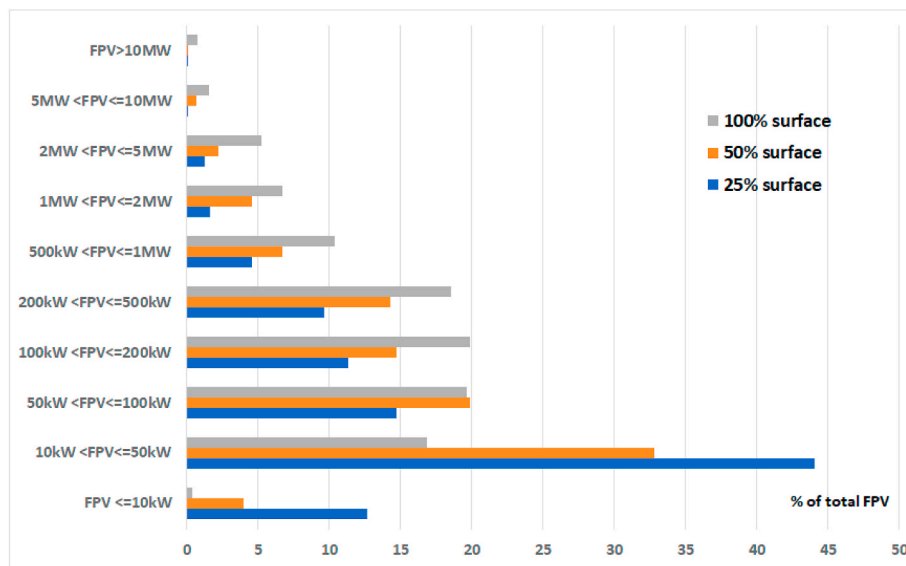


Fig. 7. FPV power size distribution.

installations lay within a power range below 200 kWp, which reinforces the idea of distributed energy source that this solution also pursues. It is highlighted the identification of a 16 MWp plant in the 25% surface area scenario, which could reach 65 MWp if 100% of the reservoir’s surface were covered.

If the previous figures for floating photovoltaic power shown in Table 4 are translated into electricity generation potential, the results of Table 5 are obtained.

In the best-case scenario, that is, no minimum power threshold and 100% of the water surface covered, up to 3142 GWh could be generated annually. In the most conservative opposite scenario ( $C_W = 25\%$  and FPV systems larger than 50 kWp), 729 GWh could be obtained, which is 1.2 times the electricity generated in 2020 in the province of Jaén accounting for all renewable systems already installed.

#### 4.2. Floating energy potential versus electricity consumption

In order to assert the significance of the data obtained, it is interesting to compare these energy results with the electricity consumption of the province, and to apply this analysis by consumption sectors.

Table 6 shows a comparison of the electricity consumption of the most representative sectors of the province. In the 3 scenarios of surface coverage of the ponds, only FPV systems with power greater than 50 kWp have been selected.

In the most favourable case, that is, using 100% of the available surface area of each pond, the total electricity consumption of the province of Jaén would be covered only with the power to be installed with floating PV systems (>50 kWp) and the consumption of the most significant sectors would be largely exceeded. On the other hand, in the most conservative scenario (25% of surface coverage), it would mean that only with the FPV power to be installed in these locations, 251% and 108% of the existing electricity consumption in the agricultural and industrial sector respectively would be achieved, whereas it could contribute up to 67% of residential consumption. In global terms, just by

Table 5  
Electricity generation (MWh) of the potential FPV systems identified.

FPV ENERGY (MWh)	100% Surface	50% Surface	25% Surface
no power	3142401.5	1571200.8	785600.4
FPV threshold			
FPV > 10 kW	3142318.0	1569760.0	781717.4
FPV > 50 kW	3117198.9	1524140.9	729174.6

Table 6

Electricity consumption coverage (%) with floating PV systems in the most representative sectors of the province of Jaén.

	Electricity consumption coverage (%)	100% Surface	50% Surface	25% Surface
FPV > 50 kWp	Agricultural	1075.77	525.99	251.64
	Industrial	465.63	227.67	108.92
	Residential	288.70	141.16	67.53
	TOTAL	116.11	56.77	27.16

using floating PV systems under the power and  $C_W$  assumptions, it would be possible to generate 27% of the province’s total electricity consumption.

Much more favourable figures are obtained if the minimum power threshold is set at FPV systems above 10 kWp. In this case, approximately one third of the total consumption would be covered ( $C_W = 25\%$ ) and up to 58% if the water surface to be occupy is 50%.

Due to the geographical dispersion of the ponds used for the identification of the floating PV potential, a more in-depth analysis has been carried out. The electricity consumed by each municipality has been compared to the potential PV generation that could be produced using only the existing irrigation ponds in those geographic districts.

Figs. 8 and 9 show the FPV generation grouped according to each municipality level, with the following assumptions: minimum FPV power threshold of 10 kWp and  $C_W = 25\%$ . In these figures, the FPV generation data have been compared with the total electricity consumption coverage percentage in Jaén (Fig. 8) and the corresponding consumption coverage ratio focused exclusively on the agricultural sector (Fig. 9).

#### 4.3. Photovoltaic land positive solution

Complementary to the generation-consumption analysis, one of the objectives of this type of floating installations is to avoid occupying land that could be used for other purposes.

For this reason, this analysis was extended to determine the area of land not necessary to occupy. This land is mostly dedicated to olive cultivation, which is the predominant crop in the province of Jaén. This calculation, as explained in the methodology, was based on the comparison with a fixed photovoltaic system, in which a tilt angle corresponding to the latitude of each pond’s location.

The results have been obtained according to two approaches. On the

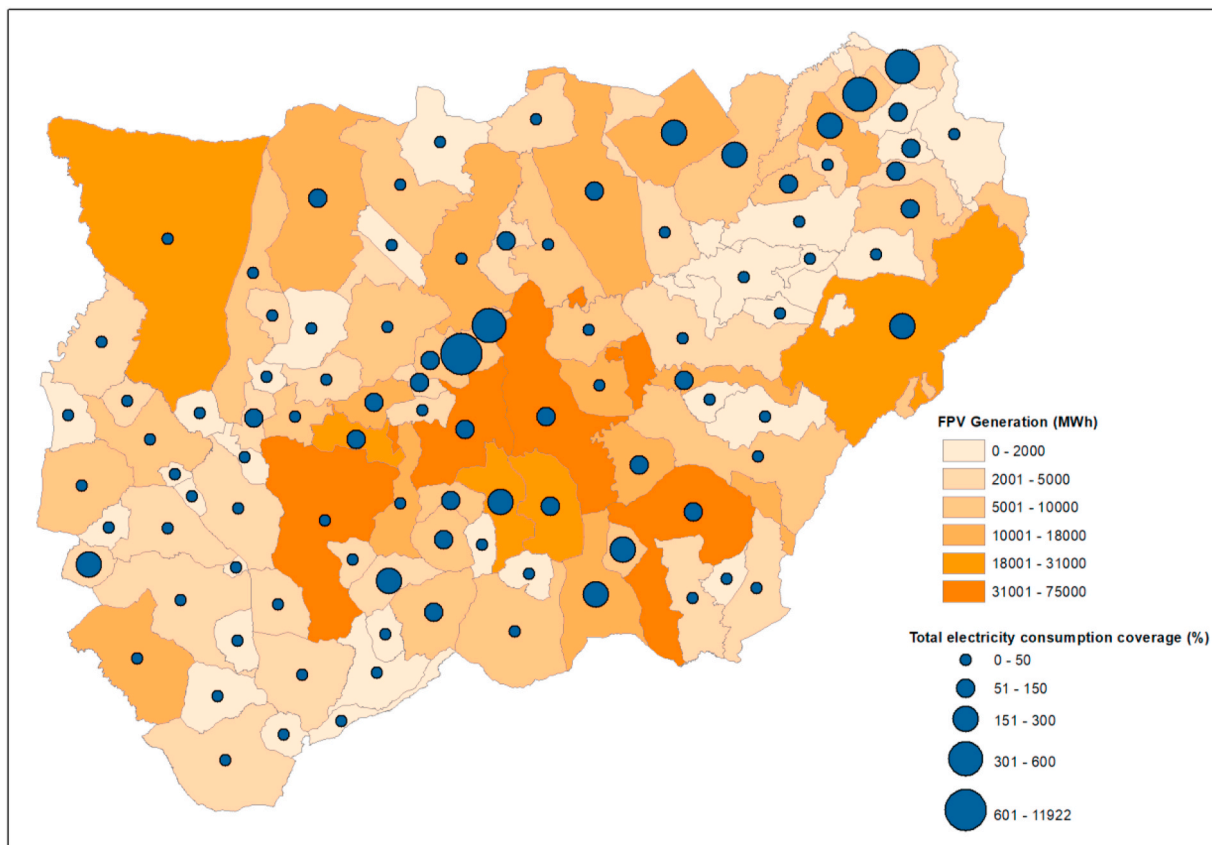


Fig. 8. Geographical distribution of the FPV generation and total electricity consumption coverage in Jaén.

one hand, the area of land that a fixed system should occupy to cover the same potential power of floating systems has been calculated (see Table 7). On the other hand, Table 8 shows the results which analyze the amount of land area required to generate the same electricity as the floating PV systems in the previous section. In this second approach, since the tilt equals to the latitude optimizes the PV generation, less power (thus less area) is needed in ground-mounted PV systems to generate the same energy than FPV.

#### 4.4. Side benefits

Delving into more benefits that these FPV systems may produce if installed in such irrigation ponds, special emphasis should be placed on avoided CO<sub>2</sub> emissions, the job creation capacity and in this particular case, the possible reduction of water evaporation. Table 9 summarises these results for the different coverage scenarios and assuming that there is no minimum power threshold for the systems to be installed.

It is outstanding that annually a minimum of approximately 9 hm<sup>3</sup> (i. e. 10<sup>6</sup> m<sup>3</sup>) of water can be saved in the most conservative scenario (C<sub>w</sub> = 25%). However, if 100% of the irrigation ponds surface is covered, 35 hm<sup>3</sup> could be saved annually, which represents 1.5% of the total water capacity of the large reservoirs existing in the province.

Another benefit of the massive FPV installation is related to job creation. Approximately 7000 jobs can be created in the most conservative scenario between the construction and Operation stages, whereas up to 29,000 jobs could be created in the most favourable situation.

## 5. Discussion and limitations of the study

In a global context where the installation of FPV systems is a growing trend, the results of this study show that their implementation on irrigation ponds is an interesting alternative and that regions such as Jaén,

in Spain, is an ideal place for its implementation, because it has 3177 irrigation ponds, and additional water structures are being planned in the short-term future.

It is highlighted that up to one third of the electricity generation needs of the province could be provided by FPV systems that only covers 25% of the available surface area of these ponds. This figure, together with the 605 GWh currently generated by renewable energy systems in the province, would mean reaching 50% electricity coverage without the need to occupy additional useable land. In the case of this study, a minimum 12 km<sup>2</sup> of land, which would have been necessary if PV systems were installed on the ground, could be saved.

This is not the only possible benefit of FPV in the region. Beside the positive CO<sub>2</sub> emissions avoided, in a region with cyclical droughts and low rainfall rates, avoiding evaporation of stored water for irrigation is a great added value. In the case of Spain, Bengoechea et al. [48] estimated that evaporation losses in agricultural water reservoirs can reach up to 17% and Santafé et al. [49] calculated a water loss reduction of 25% after the installation of a FPV system on a water irrigation pond.

Finally, the creation of jobs is an important asset, moreover in a region with high unemployment rates. In the most conservative scenario, 6800 jobs could be created during the construction of such systems and 370 could be permanently be kept for O&M tasks.

Despite the very favourable results obtained in this analysis, there are some limitations in this research that should be addressed in future work.

The limited scientific knowledge of the real performance of floating PV systems is the first limitation of this study. The influence of the temperature in the operating conditions of similar systems have not been sufficiently stated [47]. This influence may not only affect the energy results of this type of system, but also the fact that the simulation models used to calculate the energy production are not yet sufficiently adapted [50], as it could be the case of the SAM software. An analysis over time

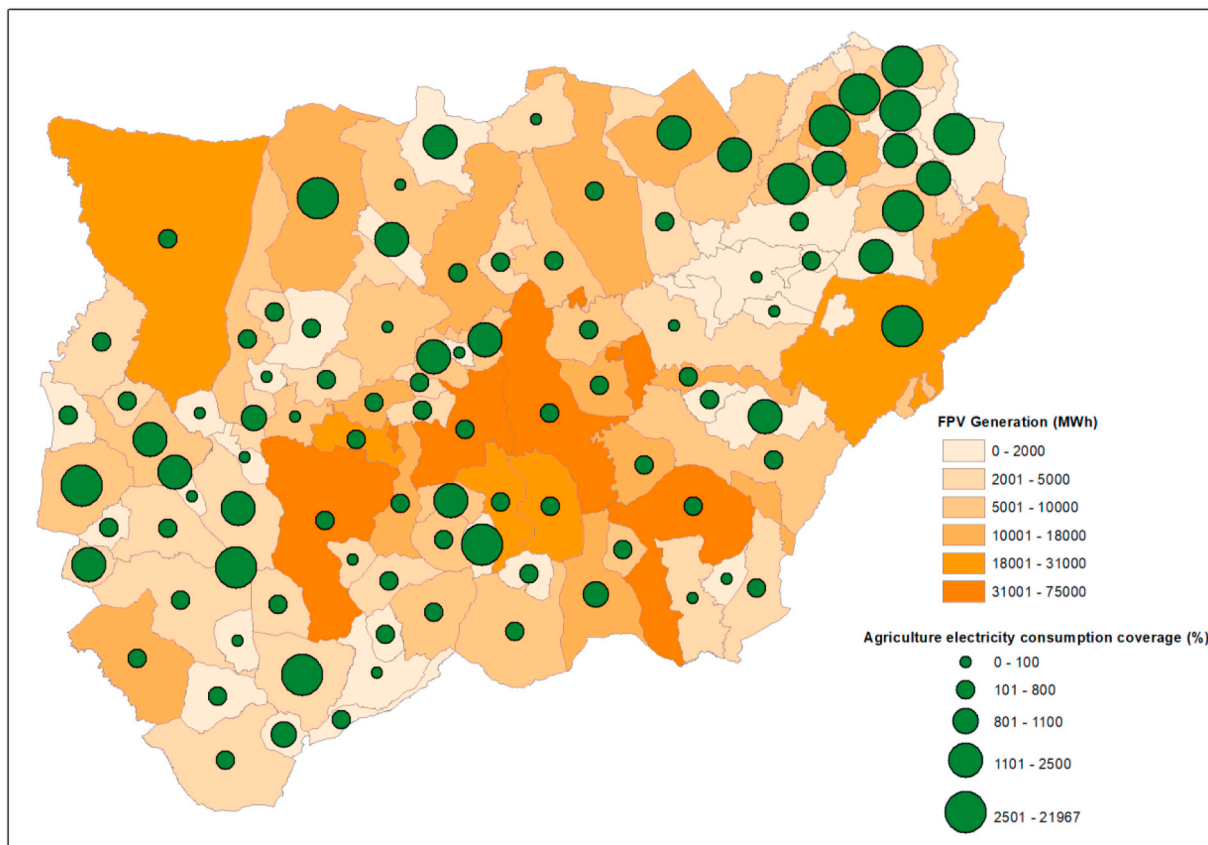


Fig. 9. Geographical distribution of the FPV generation and Agriculture sector electricity consumption coverage in Jaén.

**Table 7**  
Land requirements (km<sup>2</sup>) for the installation of ground-mounted PV systems accounting for the same FPV peak power.

Avoided land occupancy (km <sup>2</sup> )	100% Surface	50% Surface	25% Surface
no FPV power threshold	54.48	27.24	13.62
FPV > 10kWp	54.48	27.22	13.55
FPV > 50kWp	54.05	26.43	12.64

**Table 8**  
Land requirements (km<sup>2</sup>) for the installation of ground-mounted PV systems accounting for the same FPV energy generation.

Avoided land occupancy (km <sup>2</sup> )	100% Surface	50% Surface	25% Surface
no FPV power threshold	48.92	24.46	12.23
FPV > 10kWp	48.92	24.46	12.23
FPV > 50kWp	48.53	24.27	12.13

**Table 9**  
Multi benefits of the massive installation of FPV systems on irrigation ponds.

Coverage (C <sub>w</sub> ) Scenario	Avoided emissions (MtCO <sub>2</sub> /year)	Evaporation reduction (10 <sup>6</sup> m <sup>3</sup> /year)	Jobs creation in C&I	Jobs creation in O&M
100%	1.14–2.60	35.23	27,482	1480
50%	0.57–1.30	17.62	13,741	740
25%	0.29–0.65	8.81	6870	370

of the system used as a reference in this article can help to reduce the uncertainty of the results obtained.

This manuscript has been approached from an annual perspective, which is another limitation. The effect of the seasonal fluctuations in the photovoltaic generation and its comparison on the seasonal consumption should be also analyzed.

In addition to the annual analysis, this article refers to the gross potential of floating photovoltaic installations, but a more exhaustive analysis, based on GIS techniques, should be undertaken to obtain the net installation potential [51]. The experience with the installation of the pilot system, where there was some reluctance on the part of the irrigation community, suggests that aspects such as social acceptance should be taken into account, as shown by recent research carried out in the region [52].

Finally, it should not be forgotten that any study of technical feasibility and identification of the potential of any technology must be accompanied by an analysis of the economic component. There are studies that analyze in a general approach the potential of this type of systems at the European level [53] or more specifically in the case of reservoirs in Spain [22], but more realistic data would be obtained if this study descends to a more regional approach.

## 6. Conclusions

Renewable energy generation systems are the solution to promote a sustainable ecological transition. However, their implementation is not without controversy, since it involves displacing the use of land that is dedicated to agriculture or livestock farming. In the context of the high installation rates currently existing in the photovoltaic sector, there is also an increase in the number of voices against these type of systems as the implementation of large photovoltaic plants conflicts with the traditional use of the land.

In accordance with the results of studies such as the one presented in this article, it is evident that there are alternatives to the installation of PV plants on the ground, such as floating systems, since they avoid the occupation of land that could be used for agriculture.

There are numerous studies considering this type of floating systems, but only at large areas of water, such as reservoirs, which although they are an ideal location, their installation may conflict with the trophic state of the water and other uses (recreational, fishing, etc.), as well as continues to promote large centralized photovoltaic systems.

This is indeed another source of conflict with the promotion of large photovoltaic parks, because it maintains the classic energy model of creating large power generation plants, far from urban population centres, with the corresponding transmission losses.

The installation of floating photovoltaic systems in irrigation ponds a priori avoids these limitations, since these water surfaces have no other use than to store water and have a more distributed character, as reflected in the manuscript results. This characteristic allows a generation closer to the consumption points, because they either can serve to power the water pumps that are normally used in this type of installations for irrigation of adjacent areas, or are relatively close to towns and villages which may consume the energy generated.

Once the FPV potential has been identified, both in terms of photovoltaic power and electricity, it is considered necessary to continue, this study in future manuscripts from an economic perspective, since although a priori these types of systems may have a higher installation cost, they do not use land, with the consequent economic savings.

Therefore, in a scenario where farmers are facing a significant increase in electricity prices, the alternative of a renewable energy source that is able to compete with electricity supply prices is a very interesting option. Even more so when the fact of promoting these type of installations implies a positive energy land solution, meaning that it is not necessary to occupy land that is agriculturally profitable, thus representing an economic added value.

Besides improving the characterization of these type of systems, future works should also focus on analysing the hourly generation fluctuation of this type of system. This analysis will enable to assess if all the floating photovoltaic generation potential is coupled to the consumption profiles, whether global or sectoral, of the locations where they are installed, since this can significantly influence the business model of this type of project.

Finally, and due to the agricultural particularities of Andalusia, this study could be extended to the rest of the Andalusian provinces by applying the proposed methodology.

#### Credit author statement

**Emilio Muñoz-Cerón:** Conceptualization, Methodology, Formal analysis, Project Administration, Writing – original draft preparation, **Juan Carlos Osorio-Aravena:** Methodology, Formal analysis, Writing –original draft preparation, **Francisco Javier Rodríguez-Segura:** Methodology, Data curation, Visualization, Writing – original draft preparation, **Marina Frolova:** Formal analysis, Project Administration, Writing – Reviewing and Editing, **Antonio Ruano-Quesada:** Resources, Funding Acquisition.

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On the other hand, the R&D contract that the University of Jaen has

with the company Desarrollos Tecnológicos INTELEC S.L. titled “Analysis of the operation of a Floating Solar Photovoltaic Installation” been of special relevance in the data obtained in the research.

#### 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

The authors do not have permission to share data.

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## Index of notations and abbreviations

C&I:	construction and installation
CAP:	Common Agricultural Policy
Cw:	Water Coverage Percentage (%)
$E_A$ :	energy generated per unit area (kWh/m <sup>2</sup> )
$E_{FPV}$ :	Floating photovoltaic annual energy production (kWh)
FPV:	Floating photovoltaic systems
GHG:	Greenhouse gas
$K_{pVA}$ :	PV power per unit area (kWp/m <sup>2</sup> )
ktoe:	Thousand tonnes of oil equivalent (1 ktoe = 11,630 MWh)
O&M:	Operation and Maintenance
$P_{FPV}$ :	Floating photovoltaic power potential (kWp)
PV:	Photovoltaics
RE:	Renewable energy
SAM:	System Advisor Model
$S_W$ :	Water pond surface area (m <sup>2</sup> )
TMY:	Typical meteorological year (TMY)
$Y_F$ :	Final Energy Yield (kWh/kWp)