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Floating Photovoltaic Systems on Water Irrigation Ponds: Technical Potential and Multi-Benefits

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Abstract:	Floating photovoltaic systems (FPV) can be a more sustainable alternative for the energy transition than standard on-ground PV systems as they avoid the occupation of usable land. There are several FPV studies but mainly at large water bodies, i.e. reservoirs, which may conflict with the water biodiversity and other uses (recreational, fishing, etc.), and it continues the promotion of large centralized plants. FPV systems on irrigation ponds may avoid these limitations whilst enabling a generation closer to the consumption points, e.g. to power the water pumps for the irrigation facilities. However, no study focused on these more distributed locations has been found. In this context, the province of Jaén (Spain), with more than 3,000 irrigation ponds is an ideal location for such analysis. In a conservative scenario, where only 25% of these irrigation ponds surface is covered with FPV, it can provide 251% of the province agricultural electricity consumption, and 27% of the total electrical needs, avoiding the occupation of 12 km2 of usable land. It also brings additional benefits as it avoids between 0.29-0.65 MtCO2 annual emissions and 8.8·106 m3/year of water evaporated, while creating more than 6800 jobs during the construction phase and 370 during O&M tasks
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Fariborz Haghighat
Editor-In-Chief

Jaén, September 23rd, 2022

Dear Editor,

This letter is a formal request to publish the article attached, in the case you find it suitable for the aims and scopes of your journal.

The article "*Floating Photovoltaics Systems On Water Irrigation Ponds: Technical Potential and Multi-Benefits",* written by Emilio Muñoz-Cerón, Juan Carlos Osorio-Aravena, Francisco Javier Rodríguez-Segura, Marina Frolova and Antonio Ruano-Quesada, is a consequence of detecting a lack of articles and reports which deeply cover the technical potential of the novel application of floating photovoltaics at a regional level. Only 2 studies were applied to sub-national scale (regional results, both applied to Brazil) and there is not a study applied to more local level (for instance, with province/municipal results). In addition, reservoirs for hydropower generation have been the most analysed water body (included in 89% of the works) and water irrigation pond has not been evaluated alone in any single study.

In a scenario where photovoltaic technology has become the main enabler of the energy transition, social voices are raising opposing to the installation of large on-ground PV systems. Therefore, the analysis of land-positive alternatives, as Floating PV systems are, are an interesting approach.

In this manuscript, avoided GHG emission and water evaporation reduction have been additional reported indicators (beyond technical or techno-economic ones) and also job creation potential, which have not been reported until now in any floating PV manuscript until now.

Besides suggesting the reasons for publishing the paper and although I would like to show you my availability as a reviewer if you keep on finding my CV and R&D lines suitable and according to the scope of your journal.

Finally, a thoroughly review of the text spelling, grammar and style has been carried out by the official translation service of my University. However, any suggestion in order to improve the quality and readability of the paper is more than welcome.

We hope you find it interesting enough to your journal

Thanks for your attention,

PhD. Emilio Muñoz Cerón

FLOATING PHOTOVOLTAICS SYSTEMS ON WATER IRRIGATION PONDS: TECHNICAL POTENTIAL AND MULTI-BENEFITS

HIGHLIGHTS

H1 → A Technical floating PV potential assessment on water irrigation ponds is done

H2 → A Technical floating PV potential assessment at a municipal level is done

H3 → A calculation of Multi-benefits of floating PV installation is done

H4 → An energy consumption coverage assessment at municipal level with floating PV is done

Title Page (with Author Details)

FLOATING PHOTOVOLTAICS SYSTEMS ON WATER IRRIGATION PONDS: TECHNICAL POTENTIAL AND MULTI-BENEFITS

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FLOATING PHOTOVOLTAICS SYSTEMS ON WATER IRRIGATION PONDS: TECHNICAL POTENTIAL AND MULTI-BENEFITS

ABSTRACT: Floating photovoltaic systems (FPV) can be a more sustainable alternative for the energy transition than standard on-ground PV systems as they avoid the occupation of usable land. There are several FPV studies but mainly at large water bodies, i.e. reservoirs, which may conflict with the water biodiversity and other uses (recreational, fishing, etc.), and it continues the promotion of large centralized plants.

FPV systems on irrigation ponds may avoid these limitations whilst enabling a generation closer to the consumption points, e.g. to power the water pumps for the irrigation facilities. However, no study focused on these more distributed locations has been found.

In this context, the province of Jaén (Spain), with more than 3,000 irrigation ponds is an ideal location for such analysis. In a conservative scenario, where only 25% of these irrigation ponds surface is covered with FPV, it can provide 251% of the province agricultural electricity consumption, and 27% of the total electrical needs, avoiding the occupation of 12 km^2 of usable land. It also brings additional benefits as it avoids between 0.29-0.65 $MtCO_2$ annual emissions and $8.8 \cdot 10^6$ m^3/year of water evaporated, while creating more than 6800 jobs during the construction phase and 370 during O&M tasks.

Keywords: Renewable Energy; Solar Energy; Photovoltaics; Floating PV; Irrigation Ponds

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 for achieving the international climate mitigation targets (REN21, 2021). Furthermore, in the energy planning procedures it is becoming paramount to include aspects beyond the techno-economic ones (Osorio-Aravena et al., 2020), in order to implement RE technologies policies that not only reduce greenhouse gas (GHG) emission, but also that avoid others environmental problem and social conflicts whilst generating socio-economic benefits. In this sense, solar photovoltaic (PV) is one of the most promising RE technology due to its ubiquity and sustainability (Kim et al., 2019). In fact, it is projected that solar PV will be the main RE technology by 2050 (Bogdanov et al., 2021) and that will create more jobs during a climate compliant global transition across all energy sectors (Ram et al., 2022). However, concerns on environmental impacts and land use conflicts of large-scale on-ground PV plants , specifically in Spain (Serrano et al., 2020), are causing uncertainty and some opposition in the implementation of this technology.

As an alternative to these concerns, floating PV (FPV) applications are an emerging technology which has doubled its installed capacity every year (Cazzaniga & Rosa-Clot, 2021). In fact, FPV systems are cost-competitive compared to ground-mounted solar PV farms due the absence of land cost acquisition. It also provides some additional and unique characteristics, including the reduction of water evaporation of the reservoir or pond where it is installed, together with a mitigation of algae growth (Ferrer-Gisbert et al., 2013). 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 (Padilha Campos Lopes et al., 2022). Furthermore, FPV projects could mitigate climate change impacts on water body temperature and stratification (Exley et al., 2021), imply water-food-energy nexus synergies (Zhou et al., 2020), and are gaining social support (Bax et al., 2022).

1.1 Literature review

The analysis of FPV applications are an emerging topic in the scientific literature. Figure 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. Only review and research articles were considered, excluding duplicates.

As can be deducted from this figure, 62% of the manuscripts have been published from 2020 onwards (until June 12th, 2022). However, only 18 of the 195 papers (included in Figure 1) are focused on evaluating the FPV technical potential at different territorial scales.

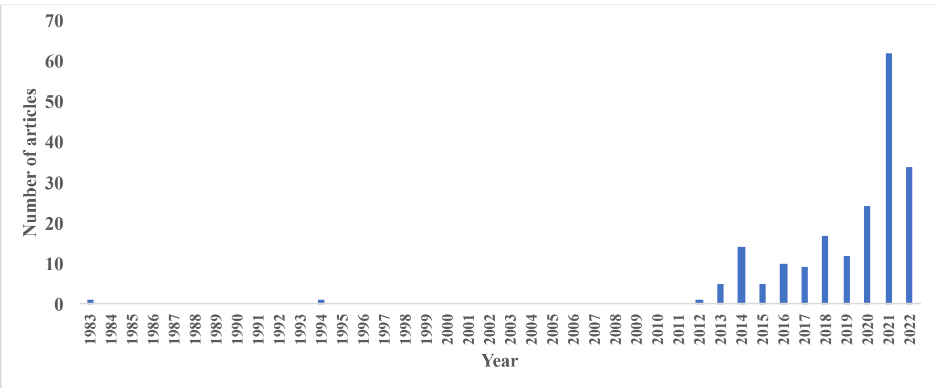

Figure 1. Number of FPV scientific articles indexed in SCOPUS and WoS databases

Table 1 summarised the research articles that assess the FPV technical potential at different territorial scales and types of water bodies. 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 2 studies were applied to sub-national scale (regional results, both applied to Brazil). To the best of the authors' knowledge, there is not a study applied focused on a more local level (for instance, with province/municipal results).

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

Beyond the technical and techno-economic indicators, the additional reported factors have been focused on avoiding GHG emission and water evaporation reduction, but these aspects are not included in all articles. However, to the best of the authors' knowledge, there have not been any published manuscript concerning the jobs creation related to floating PV projects.

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	Reservoir (water supply)	Irrigation pond	Industrial pond	CO_2 emission	Evaporation reduction

			generation)				reductio n	
Perez et al. (Perez et al., 2018)	National	x	x					x
Farfan and Breyer (Farfan & Breyer, 2018)	Global		x					x
Tina et al. (Tina et al., 2018)	Global	x	x	x	x	x		
Kim et al. (Kim et al., 2019)	National	x	x	x			x	
Château et al. (Château	National					x		

et al., 2019)								
Spencer et al. (Spencer et al., 2019)	National		x	x	x			x
Campos et al. (Padilha Campos Lopes et al., 2020)	Sub-national			x				x
Zubair et al. (Zubair et al., 2020)	National	x	x	x				
Stiubiener et al. (Stiubiener et al., 2020)	National		x					

Micheli (Micheli, 2021)	National		x	x	x			
Muhammad et al. (Muhammad et al., 2021)	National	x	x	x	x			
Quaranta et al. (Quaranta et al., 2021)	Continental		x					
Gonzalez et al. (Gonzalez Sanchez et al., 2021)	Continental		x					x
Sulaeman et al. (Sulaem	National		x					

an et al., 2021)								
Ravichandran et al. (Ravichandran et al., 2021)	National		x				x	x
Moraes et al. (Moraes et al., 2022)	Sub-national		x				x	x
López et al. (López et al., 2022)	National	x	x	x			x	
Campos et al. (Padilha Campos Lopes et	National		x	x	x	x		

al., 2022)								

1.2 Aim and contribution of this research work

The aim 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). An estimation of its multi-benefits is also considered in order to provide objective information beyond the techno-economic ones. This approach could help to energy planning processes and enabling decision-makers to accelerate the implementation of PV technology in a more sustainable manner.

Jaén's province has been used as case study because it is a territory with unexploited good solar condition, pronounced unbalance between its inner electricity production and consumption, and a significant agriculture sector based on olive crops that request water irrigation to keep its productivity.

The multi-benefits analysis included are the estimation of the avoided land used for the same capacity and electricity generation of the FPV technical potential calculation and its level of matching electricity demand from agriculture sector at the municipal and province level.

The avoided annual CO_2 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 contribution and novelty of this research can be summarised as follows: i) this is the first study that calculate the FPV technical potential at province/municipality level (sub-

sub-national scale) and only focused on water irrigation ponds; ii) this the first work that reports jobs creation of the FPV technical potential, and; iii) it is the first time that the FPV technical potential is analysed and compared with the electricity demand from different sectors (agriculture, residential, etc.) at municipal level.

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 and discussed in Section 4. Finally, in Section 5, conclusions remark of this work are exposed.

2 CONTEXTUALIZATION OF THE STUDY CASE LOCATION

The context in which the current study is applied is detailed below, starting with a description of the energy situation in the province of Jaén, which will then 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 floating system existing in the province has been installed and which has been taken as a reference for this study.

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 a land area of 13496 km^2 and it is divided in 97 municipalities. This province is characterized by being an eminently agricultural region, where the olive grove is the largest crop.

The final electricity consumption in Andalusia amounted to 2,912.0 ktoe in 2020. For that year, in the province of Jaén, consumption was 229.3 ktoe, representing 7.86 % of the Andalusian total (Agencia Andaluza de la Energía, 2022).

Disaggregating this consumption according to different economic sectors, the highest electricity consumption in the province of 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%), both sectors with similar figures. On the other hand, the primary sector and transport were the activities that consumed the least electricity, with 24.8 ktoe (10.5%) and 0.5 ktoe respectively (Agencia Andaluza de la Energía, 2022). Table 2 shows the consumption information by sector.

In the province of Jaén there has been, in recent years, a decrease in the final provincial electricity consumption, from 274.2 ktoe in 2005, to 229.3 ktoe recorded in 2020 (Agencia Andaluza de la Energía, 2022). 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 is compared with the total gross electricity production in the province of Jaén, which for 2020 was 1,723.8 GWh (148.15 ktoe), it shows a negative electricity balance between production and consumption of 81.1 ktoe. It could be stated that it is a province that is energetically dependent on other neighboring provinces.

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

	ANDALUSIA (GWh)	JAEN PROVINCE (GWh)
AGRICULTURE	1,517.23	289.76
INDUSTRY	8,391.19	669.46
BUSINESS – SERVICES	6,081.36	361.42
RESIDENTIAL	13,198.92	1,079.72
ADMINISTRATION-PUBLIC SERVICES	3,718.21	262.55
OTHER	337.40	21.83
TOTAL	**33,244.31**	**2,684.73**

Accordingly to 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. Figure 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.

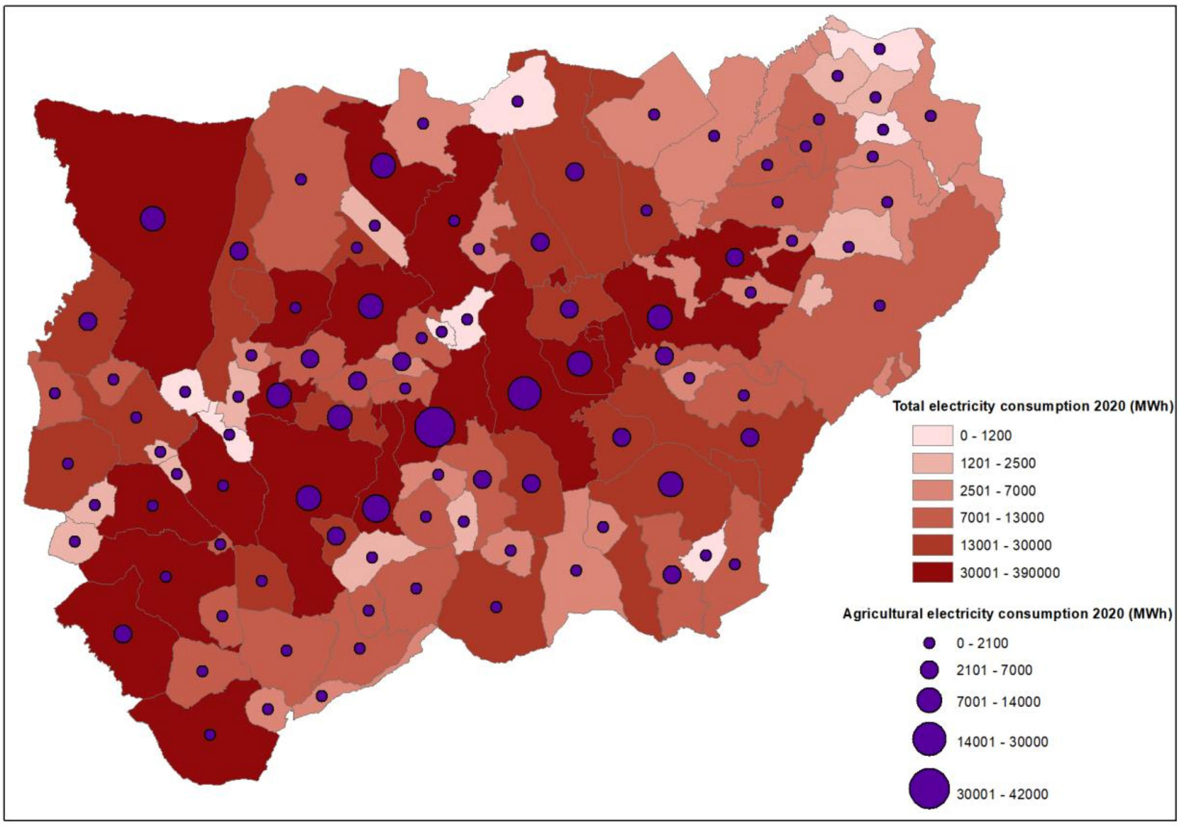

Figure 2. Total and agricultural electricity consumption by municipality in the province of Jaén

In terms of electricity generation, in 2021 the province of 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 (Agencia Andaluza de la Energía, 2021) (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 the largest being 11.8 MW. Despite this installed capacity, the renewable electricity generated in the province of Jaén only accounts for 28.9% of the total final energy consumption in the province, estimated for 2021 at 229.3 ktoe (Agencia Andaluza de la Energía, 2021). In addition, there are no fossil fuel or pumped hydroelectric generation facilities in the province, so the electricity generation system is based entirely on renewable energy systems and cogeneration plants (Agencia Andaluza de la Energía, 2021) and most of the electrical consumption of the province has to be imported from the surrounding provinces.

Table 3. Installed capacity and renewable electricity generation in the province of Jaén by 2020

	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

2.2 Irrigation ponds in the province of Jaén

The main driver of agricultural modernization processes has been the intensive use of available resources (Peñalver et al., 2015). In Andalusia, the conditioning factors of the Mediterranean climate, characterized by irregular and scarce rainfall and high transpiration, make water a limited resource disputed between domestic use and the expansion of irrigation that in the specific case of this province has experienced in recent decades (Paniza Cabrera et al., 2015).

Since the second half of the 20th century, continuous political interventions were carried out in the province of Jaén aimed at expanding the irrigated area and materialized in the construction of an extensive network of reservoirs along the Guadalquivir River and its main branches (Araque-Jiménez et al., 2002). 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 the province of Jaén (Araque-Jiménez et al., 2002). In this new context, the existing hydraulic infrastructures for irrigation were insufficient, giving rise to a proliferation of water ponds in private farms, similar to the one shown in Figure 3, that aim to optimize the use of water for irrigation and guarantee the water supply to their crops in summer drought seasons (Peñalver et al., 2015).

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

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 (Peñalver et al., 2015).

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

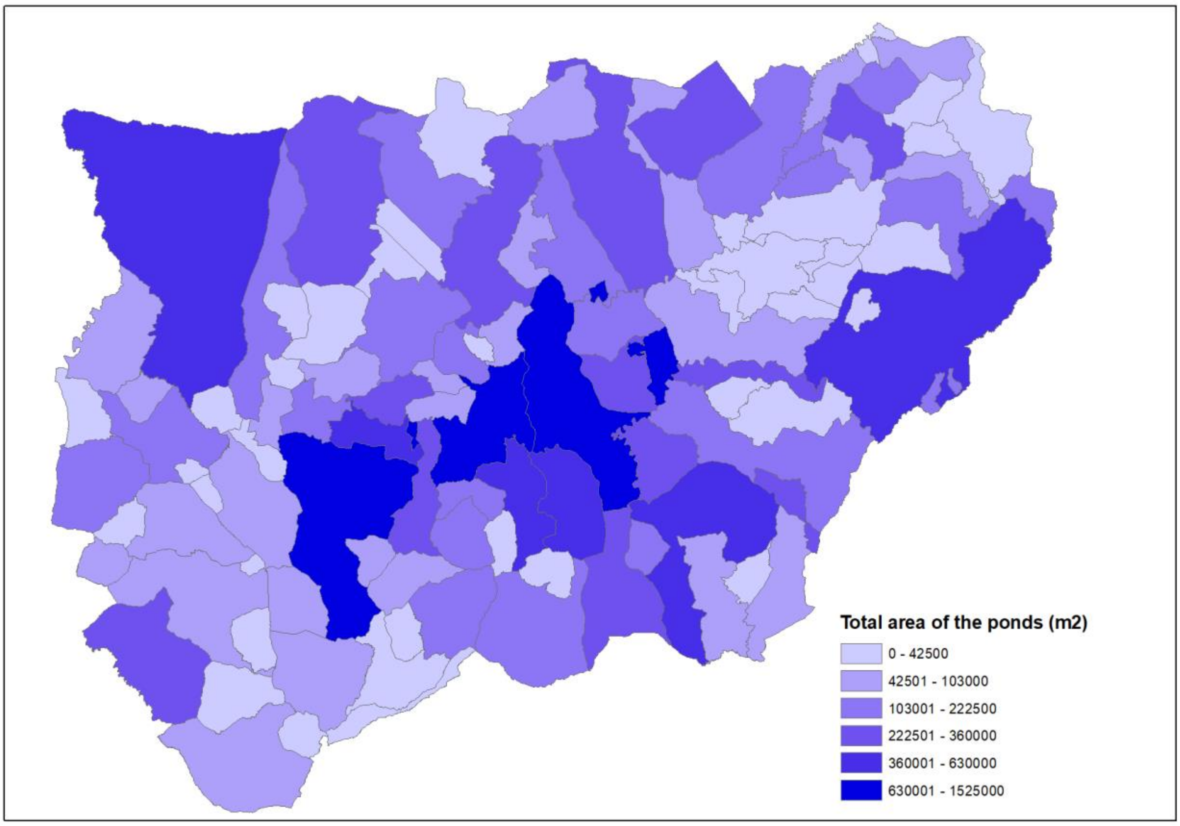

Figure 4. Water Irrigation Pond area identified for each municipality in Jaén

3 METHODOLOGY

The methodology followed in this article for the calculation of the technical potential for the installation of FPV systems using exclusively existing irrigation ponds, as well as the identification and quantification of additional benefits that the installation of this type of systems could have, is described below.

In this manuscript, only artificial water infrastructures are analysed, therefore, natural lakes for the potential PV identification were not considered. Furthermore, unlike similar studies in

Spain (López et al., 2022), this research has also excluded water surfaces belonging to reservoirs. It has only focused on identifying those water accumulation surfaces oriented to agricultural irrigation activities, since the installation of PV systems in such locations does not conflict with other uses (recreational, fishing) that can be found in reservoirs. In addition, water irrigation ponds are not affected by the area limit which may imposed the future Spanish legislation (now in public consultation stage), as several surface coverage limits (up to 20% maximum) are set according to the trophic state of the reservoir (*Real Decreto XXX/200X, de XX de XX, Por El Que Se Establece El Régimen de Instalación de Plantas Fotovoltaicas Flotantes En El Dominio Público Hidráulico*, 2022).

To calculate the potential for electricity generation in the province of Jaén from floating solar photovoltaic systems on water infrastructure, all ponds dedicated to olive tree crops were quantified from the cartographic data provided by the Multiterritorial Information System (Instituto de Estadística y Cartografía de Andalucía, 2022).

The geospatial processing software ArcMap was used for this purpose. Once the facilities were classified by municipalities, the perimeter and surface area of each one was measured, as well as their respective central point (centroid), used as a reference to calculate their geographic coordinates and thus georeference their location. In this identification, only water irrigation ponds were considered, whereas the ponds dedicated to the toxic liquid waste resulting from pressing the olives to make oil have been ignored.

In the same way, the central point (centroid) of all ponds within a certain municipality was calculated through ArcMap software and from its surface extension, whose coordinates were used as a reference to obtain the radiation data of all the potential FPV plants to be located in that municipality. An independent meteorological file has been obtained for each of the centroid locations, corresponding to the typical meteorological year (TMY). For this purpose, the PVGIS tool (version 5.2) which provides solar radiation database has been used. In this research, the database PVGIS-SARAH2 has been considered, whose data are satellite based and covers a time span from 2005 to 2020 (Huld et al., 2012).

The performance of a reference FPV system for each of the 94 aggregated sites where all ponds identified are disseminated have been simulated using NREL software SAM (Spencer et al., 2019) and the TMY files obtained in the previous step. The overall losses of the PV system have not been modified, because although there are several authors who mention possible gains due to the cooling effect of the water, these measures are not yet sufficiently contrasted and in some cases, depending on the type of floater used, the improvements are not so high (Dörenkämper et al., 2021). These improvements could also be counteracted by the effect of dirt, especially from bird drops, as the isolation of these locations tend to be more prone to the accumulation of this type of dirt. Therefore, in a first approximation, it has been considered appropriate to set the system's global losses as the software’s default.

The final energy yield (Y_F, kWh/kWp) of a reference system with 5º tilt angle, similar as the one already installed (see Figure 5) have been simulated for each of the 3177 irrigation ponds identified. In addition, for comparison purposes, a twin system but with the optimal tilt angle was also simulated for each location, i.e. tilt angle matching the latitude of the site.

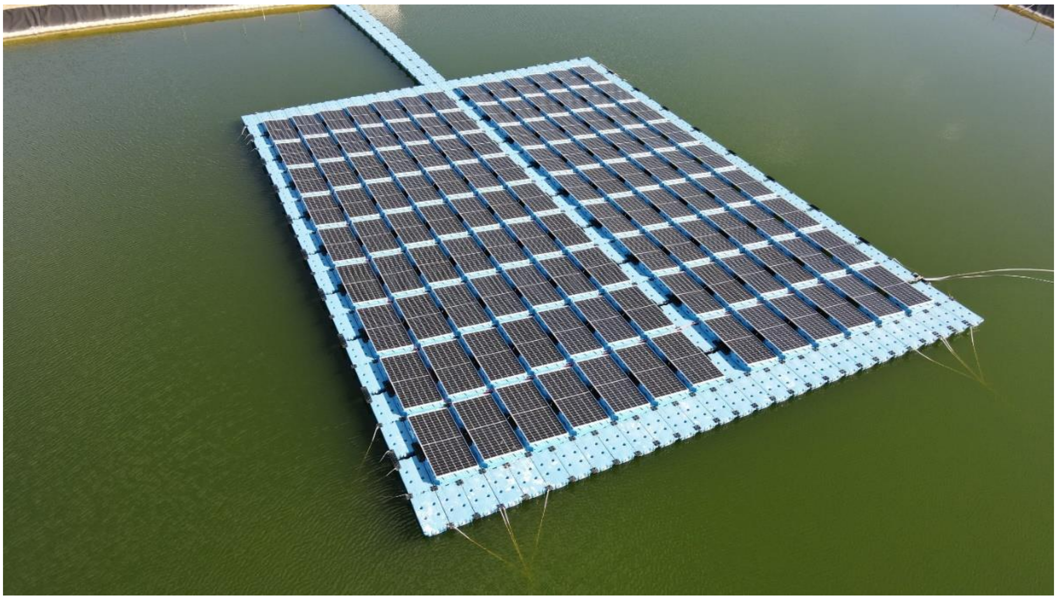

Figure 5. First FPV plant installed in the province of Jaen by Desarrollos Tecnológicos Intelec S.L

Subsequently, the energy per unit area (E_A, kWh/m^2) of both a floating PV system and a fixed one with optimal tilt angle has been calculated. For such purpose, the power per unit area (P_A, kWp/m^2) and the energy yield (Y_F) need to be provided for each system. The peak power and the water surface covered of the already FPV installed in Jaén (see Figure 5) has been used as reference for such calculation in the case of the FPV system. In this FPV plant, 52.7 kWp were installed, occupying a surface of 401m^2, therefore, the power per unit area considered in this research is 0.131 kWp/m^2, so accounting for the annual energy yield simulated for each system, the energy per unit area can then be calculated according to the following formula:

$$E_A(kWh/m^2) = P_A(kWp/m^2) \cdot Y_F\,(kWh/kWp) \qquad (1)$$

The estimated power per unit area (kWp/m^2) considered for fixed PV plants was obtained from real installation information available at the repertoire of 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 (Instituto de Estadística y Cartografía de Andalucía, 2014). Accounting for 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 power per unit area of 0.388 MWp/ha has been obtained. Likewise FPV systems, the energy per unit area can then be calculated according to equation 1.

For each of the 3177 irrigation ponds identified, three analysis scenarios related to the surface area of the pond covered by the floating system have been proposed. Starting with the most optimistic case, which, although not realistic, is indicative of the maximum value to be obtained, it has been considered that 100% of the water pond area (S_W, m2) is covered by this type of FPV systems. Subsequently, it has been set a coverage percentage of 50% and finally 25%. For this last value, the minimum level of the pond under study (figures 3 and 5) has been taken as a reference, which matches with the floor of the pond (absence of water). In this installation, the floats used are designed to rest on the surface of the pond without damaging its waterproofing layer.

Considering these water surface occupancy scenarios, and the previous power and energy densities values, the next step was to obtain the power and annual energy production of each of the 3177 ponds recorded in the province (see equations 2 and 3)

$$P_{FPV} = P_A(kWp/m^2) \cdot S_W\ (m^2) \qquad (2)$$

$$E_{FPV} = E_A(kWh/m^2) \cdot S_W\ (m^2) \qquad (3)$$

According to the methodology described, there is no minimum FPV system size. This approach may distort the results obtained, since it could be the case that there are numerous very small irrigation ponds that in practice cannot be executed because they lack of either technical or economic viability. For this reason, a filter has been applied that introduces a minimum power to be installed in the localized ponds. This filter has been firstly set at 10kW and in a second approximation at 50kW, to resemble the size of the plant taken as a reference (Figure 5).

Once the photovoltaic generation was obtained for each pond under the scenarios and filters previously mentioned, these electricity production results have been compared with the electricity consumption information from Table 2. Besides the provincial approach, this comparison has also been extended to a municipal level where there are irrigation ponds (94 out of 97), extending the comparison on the percentage of electricity consumption that this type of facility would cover at each municipality level. Therefore, all results from the 3177 FPV systems to be installed in the irrigation ponds identified, have been aggregated to the 94 municipalities defined.

In addition, for the purpose of analyzing the impact of the results, it is not only interesting to obtain information on the potential (power and energy) for the installation of floating PV systems and their electrical coverage with respect to the current system, but also to study the surface for olive crops that has been prevented from being occupied by photovoltaic plants. To this end, two analysis strategies have been proposed. On the one hand, the surface area that a fixed system (with its optimum inclination) would need to occupy to achieve the same power as the floating systems obtained is considered, while the other analysis scenario consists of determining the surface area that this type of on-ground system would need to produce the same amount of energy as that generated by the floating installations.

Beyond the electrical and land occupation benefits, this sort of initiatives also brings side positive effects. In this manuscript, these benefits have been focused on job creation, CO_2 emissions avoidance and reduction of water evaporation due to the surface covered by the PV modules and floaters.

To estimate the direct jobs creation for the total FPV in the construction and installation (C&I) stage and for operation and maintenance (O&M) purposing, the following employment factors were used: 13 jobs/MWp and 0.7 jobs/MWp for C&I and O&M, respectively, according to Ram et al (Ram et al., 2022).

Regarding CO_2 emissions reduction estimation, 0.364–0.826 ktCO_2/GWh was considered, which is the range of CO_2 emission factor relying on the specific fossil fuel-based electricity generation technology (Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T., Tanabe, n.d.).

Finally, to estimate the reduction of water evaporation by covering the irrigation pond with FPV systems, it was used a factor based on the annual values reported by Santafé et al. (Santafé et al., 2014): 16,667 m^3/MWp.

4 RESULTS AND DISCUSSION

According to the sort of water infrastructures filter imposed in the methodology section, 3177 water irrigation ponds have been identified in the province of Jaén for the installation of FPV systems, with a total surface of 16 km^2.

For each irrigation pond located, the potential FPV power to be installed has been calculated according to the coverage scenario described in the methodology section. Once the results have been aggregated for each municipally, the overall figures have been obtained.

Table 4 shows the results for this research. In order to avoid FPV systems that can distort the results, a minimum threshold for the PV plant power has also been included. It can be observed that in the idealistic case, where 100% of the water surface is covered and no minimum FPV power is required, 2.1 GWp could be potentially be installed in this region just using the existing irrigation ponds.

At the other end of the analysis range would be the more conservative situation of using only 25% of the total available surface area in each irrigation pond and only taking into account those photovoltaic systems whose peak power is greater than 50 kW. In this case, up to 490 MWp could be installed, which assuming a DC/AC ratio of 1.2 would mean 408 MW, representing 2.6 times the current PV capacity existing in the province of Jaén, and approximately matching the current renewable energy power installed in the province, according to the data from 2020.

In the middle range would be a scenario that technically could be implemented in the most realistic case, i.e., considering only systems of more than 50 kWp and covering up to 50% of the water surface area. In this case, FPV systems totalling 1 GWp could be potentially installed, which represents 5.4 times the existing PV capacity of the province based on a DC/AC ratio of 1.2.

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

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

These results depends not only on the percentage of water surface covered, but also on the FPV system size. Figure 6 shows the distribution of FPV power system size depending on the percentage of surface covered. As the available surface area is reduced, the homogeneity in the distribution of systems shifts towards the existence of systems with lower powers. In any case, most of the installations lay within a power range below 200 kWp, which reinforce the idea of distributed source of energy 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 were covered.

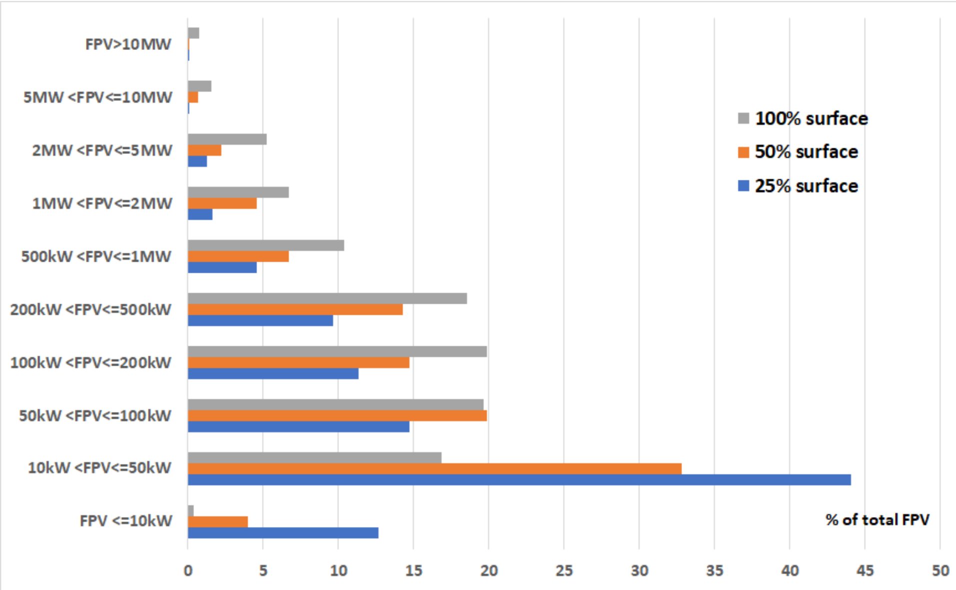

Figure 6. FPV power size distribution

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.

Table 5. Electricity generation of the potential FPV systems identified

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

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. On the opposite most conservative scenario (25% surface 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.

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 extending this analysis by consumption sectors.

Table 6 shows the comparative coverage of electricity consumption for the most representative sectors of the province. Only FPV systems with power greater than 50 kWp have been selected under the 3 scenarios of surface coverage of the ponds.

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 just 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 where only 25% of the surface area of each pond is used, 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 would be able to provide up to 67% of residential consumption. In global terms, only by using floating PV systems it would be possible to cover 27% of the province's total electricity consumption.

Much more favourable figures are obtained if the minimum power threshold is set to FPV systems larger than 10 kWp. In this case, about one third of the total consumption will be covered when using just the 25% of the surface and up to 58% if the water surface to be occupy is 50%.

Table 6. Electricity consumption coverage with floating PV systems in the most representative sectors

FPV > 50 kWp	100% Surface	50% Surface	25% Surface
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 %

Due to the geographical dispersion of the ponds used for the identification of the floating PV power potential, a more in-depth analysis has been carried out. The total electrical power 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.

In this analysis, where the most conservative surface scenario has been chosen, Figure 7 and 8 show the FPV generation at each municipality level, with the following assumptions: 10 kWp minimum FPV power threshold and 25% of water surface coverage. In this figures, these generation data have been compared with the total electricity consumption coverage in Jaén (Figure 7) and the percentage of the agricultural sector consumption covered (Figure 8).

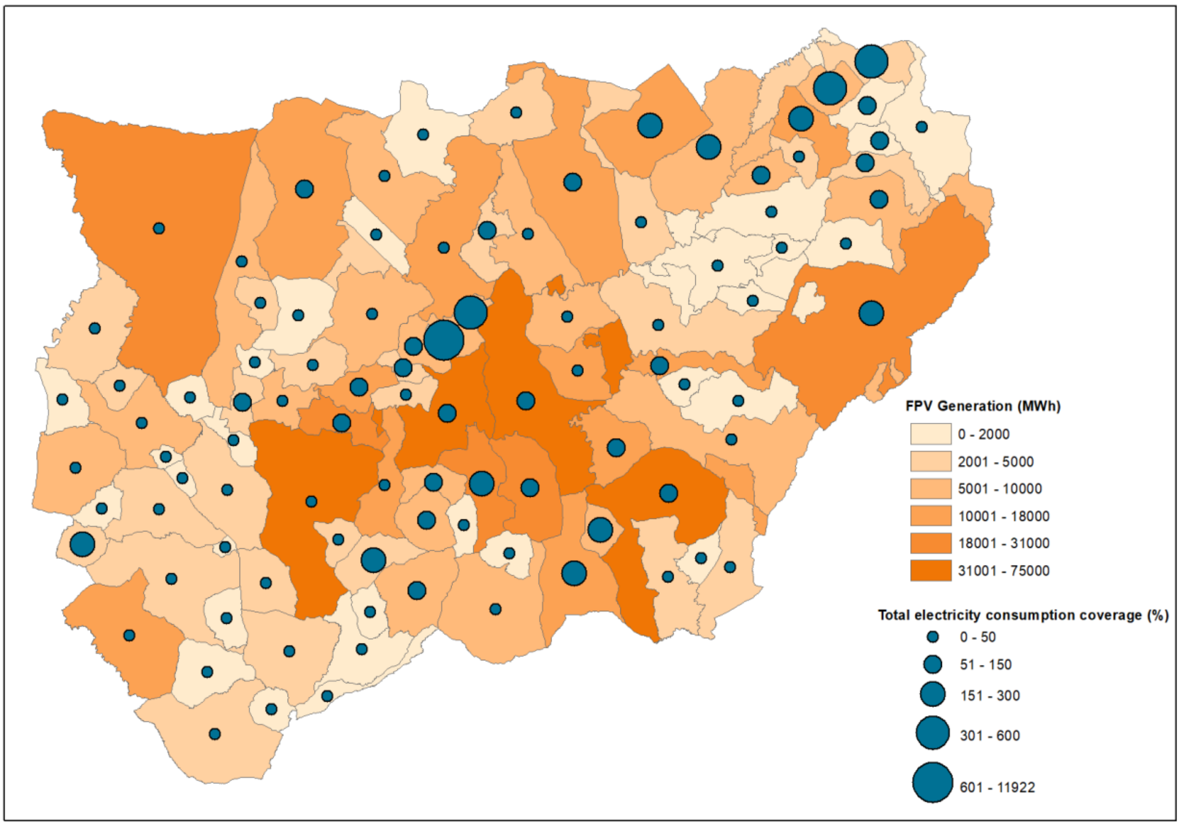

Figure 7. Geographical distribution of the FPV generation and total electricity consumption coverage in Jaén.

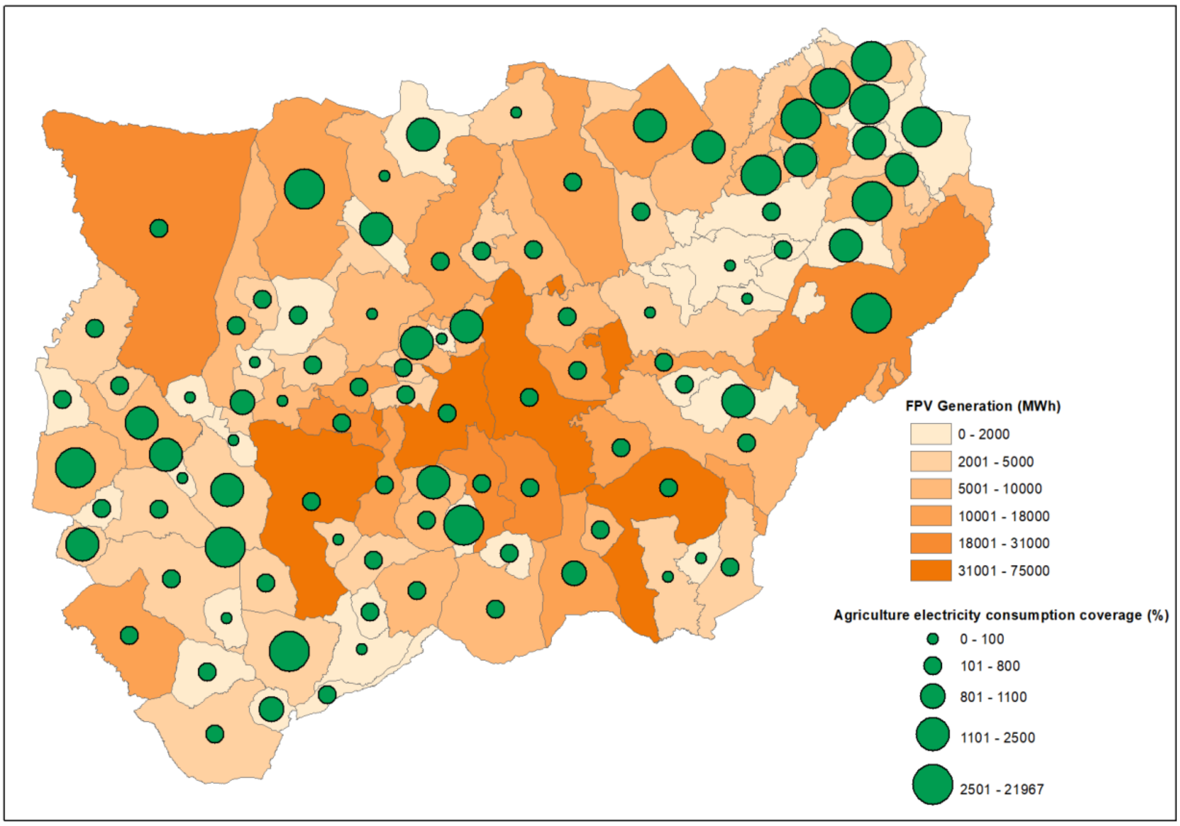

Figure 8. Geographical distribution of the FPV generation and Agriculture sector electricity consumption coverage in Jaén.

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

Therefore the analysis of the potential for the installation of floating systems has been extended to determine the on-ground surface avoided to occupy, mostly dedicated to olive cultivation, which is the predominant crop in the province of Jaén. This calculation, as explained in the methodology, has been based on a comparison with a fixed photovoltaic system, where an angle of inclination equal to the latitude corresponding to the location of each raft has been defined.

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

In addition, the results have also been obtained to analyse the quantity of land area needed to generate the same electricity as the floating PV systems (see Table 8). In this second approach, since the inclination equals to the latitude optimizes the PV generation, at ground-mounted PV systems less power (thus less area) is needed to obtain the same energy than FPV.

Table 7. On-ground PV land necessity for the same FPV peak power

	100% Surface	**50% Surface**	**25% Surface**
(no power FPV threshold)	54.48 km^2	27.24 km^2	13.62 km^2
FPV > 10kW	54.48 km^2	27.22 km^2	13.55 km^2
FPV > 50kW	54.05 km^2	26.43 km^2	12.64 km^2

Table 8. On-ground PV land necessity for the same FPV energy generation

	100% Surface	**50% Surface**	**25% Surface**
(no power FPV threshold)	48.92 km^2	24.46 km^2	12.23 km^2
FPV > 10kW	48.92 km^2	24.46 km^2	12.23 km^2
FPV > 50kW	48.53 km^2	24.27 km^2	12.13 km^2

Delving into more benefits that these FPV systems may have if installed in such irrigation ponds, special focus has to be made to the avoided CO_2 emissions, the job creation capacity and in this particular case, the possible water evaporation reduction. Table 9 summarises these results for the different coverage scenarios and assuming no minimum power threshold for the systems to be installed.

Beside the positive CO_2 avoided emissions, it is outstanding that annually a minimum of c.a 9 hm^3 (i.e. 10^6 m^3) of water can be saved. However, if 100% of the irrigation ponds surface is covered, 35 hm^3 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.

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

Scenario	**Avoided emissions ($MtCO_2$/year)**	**Evaporation reduction (10^6 m^3 / year)**	**Job creation in C&I (Jobs)**	**Job creation in O&M (Jobs)**
100% FPV	1.14–2.60	35.23	27,482	1,480
50% FPV	0.57–1.30	17.62	13,741	740
25% FPV	0.29–0.65	8.81	6,870	370

5 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 an increase in the number of voices against these type of systems. This is a major reason to support solutions such as floating photovoltaic systems, as they can be an alternative that avoids the use of land, while generating renewable electricity in a more distributed way than large centralised on-ground PV systems.

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

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, which would allow a generation closer to consumption points, as it is the case that they can serve to power the water pumps that are normally used in this type of installations for irrigation of adjacent areas.

In this context, the province of Jaén is an ideal location for the implementation of this type of solution, since it has 3,177 irrigation ponds and additional water structures are being planned in the short-term future.

It should be noted that only covering 25% of the available surface area of the irrigation ponds could generate up to one third of the electricity generation needs of the province. 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 usable land.

This is not the only benefit of the application of this solution in the region. Beside the positive CO_2 avoided emissions, in a region where cyclical droughts, as well as a generalized low rainfall exist, avoiding evaporation of stored water for irrigation is a great added value. According to the results, between 8.8 and 35 hm^3 of water could be saved annually from being evaporated. In the case of Spain, Bengoechea et al. (Bengoechea et al., 1991) estimated that evaporation losses in agricultural water reservoirs can reach up to 17% and Santafé et al. (Redón Santafé et al., 2014) calculated a water loss reduction of 25% after the installation of a floating PV 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 could be created during the construction of such systems and 370 could be permanently be kept for O&M tasks.

Once the potential has been identified, both in terms of photovoltaic power and electricity generation, it is considered necessary to continue, in future manuscripts, this study 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. In the case of this study, the occupation of up to 50 km^2 has been avoided in the most favourable case, or 12 km^2 in the most conservative scenario of electricity generation with fixed systems that produce the same amount of energy.

Therefore, in a scenario where farmers are facing a significant increase in electricity prices in order to maintain their crop irrigation systems, the alternative of being able to install 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 this type of installation 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.

Due to the agricultural particularities of Andalusia, this study could be extended to the rest of the Andalusian provinces by applying the proposed methodology, where it is expected that interesting results could be obtained.

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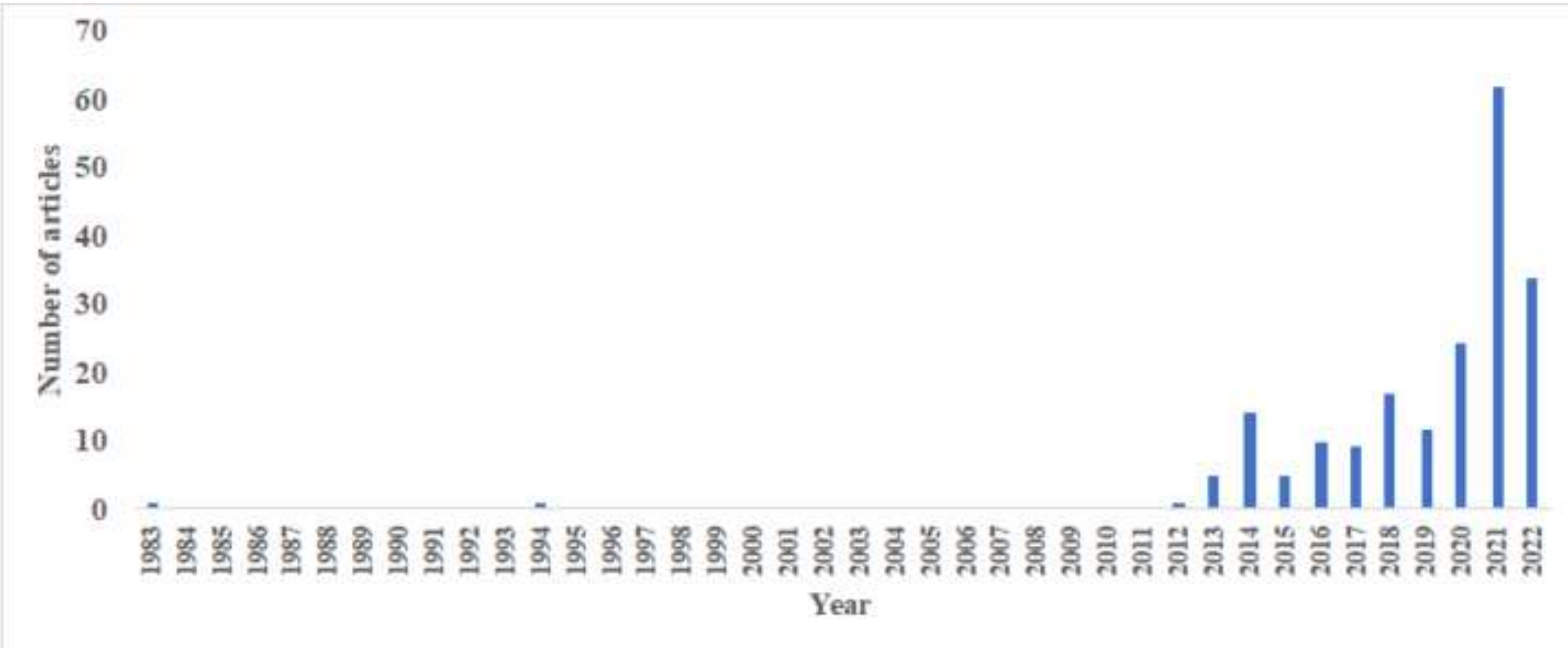
Figure 1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Number of articles
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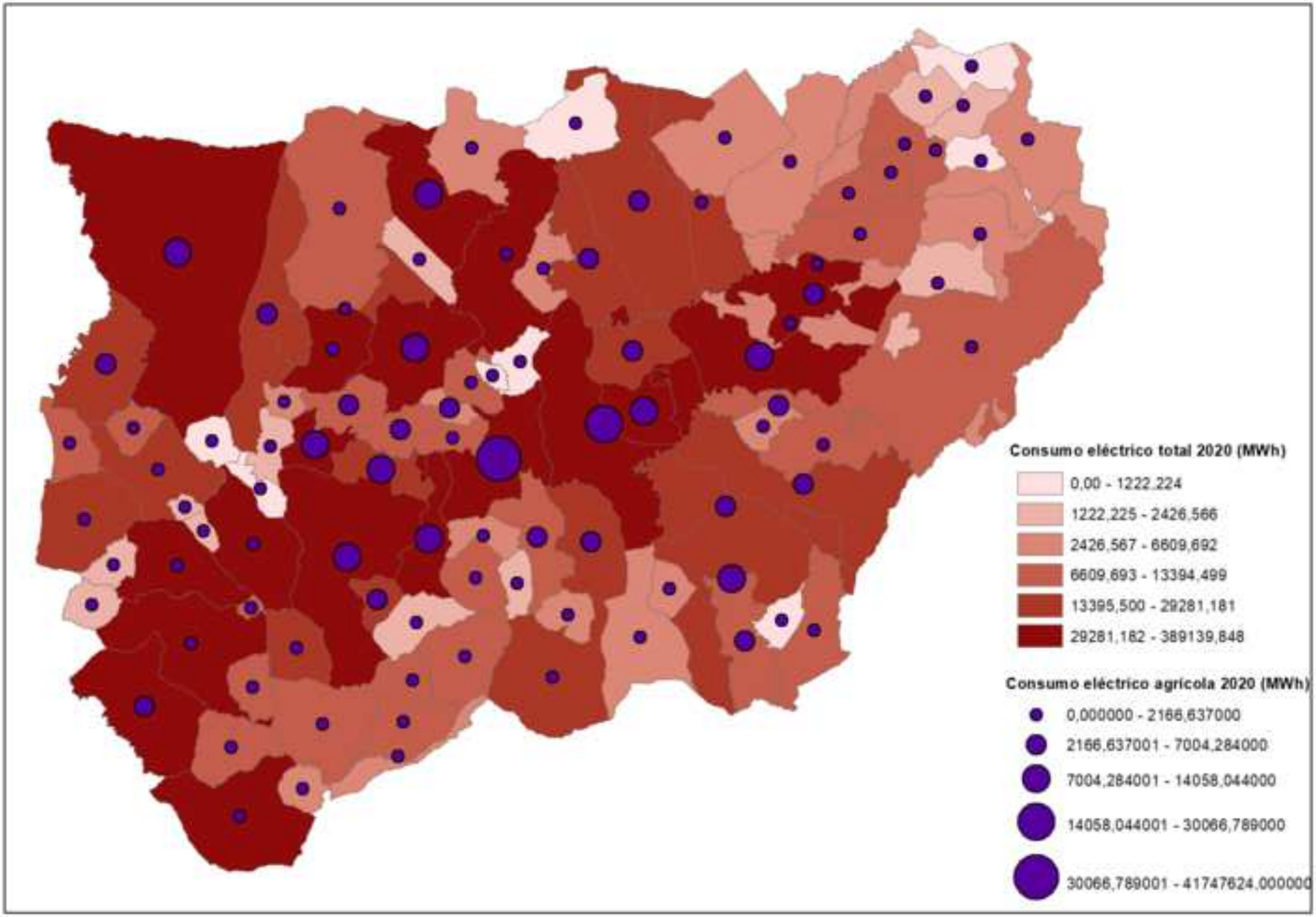
2022
Year

Figure 2


Consumo eléctrico total 2020 (MWh)
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1222,225 - 2426,566
2426,567 - 6609,692
6609,693 - 13394,499
13395,500 - 29281,181
29281,182 - 389139,848
Consumo eléctrico agricola 2020 (MWh)
0,000000 - 2166,637000
2166,637001 - 7004,284000
7004,284001 - 14058,044000
14058,044001 - 30066,789000
30066,789001 - 41747624,000000

Figure 3

Figure 4

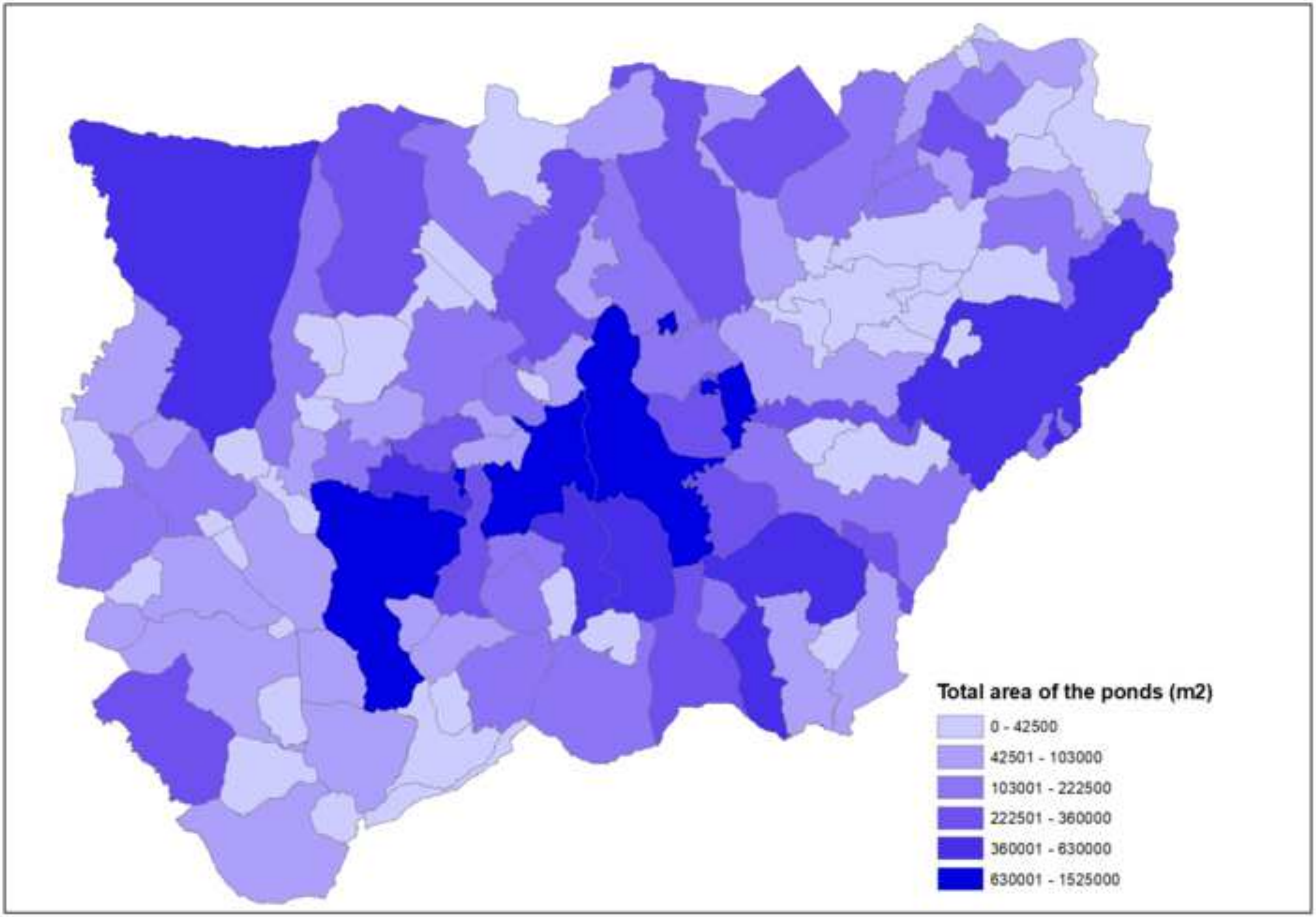
Total area of the ponds (m2)
0 - 42500
42501 - 103000
103001 - 222500
222501 - 360000
360001 - 630000
630001 - 1525000

Figure 5

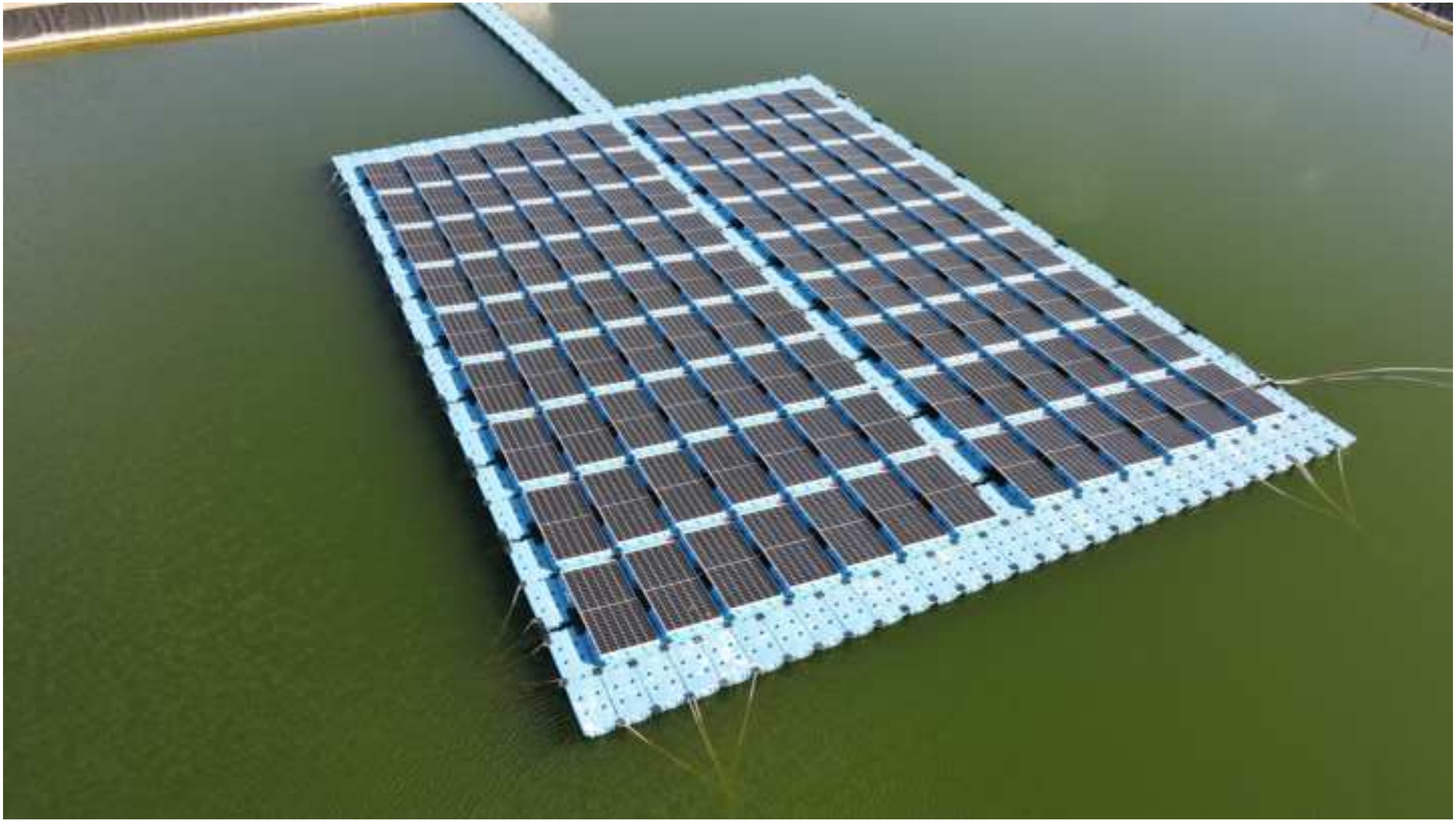

Figure 6

Click here to access/download;Figure;Figure 6.tiff

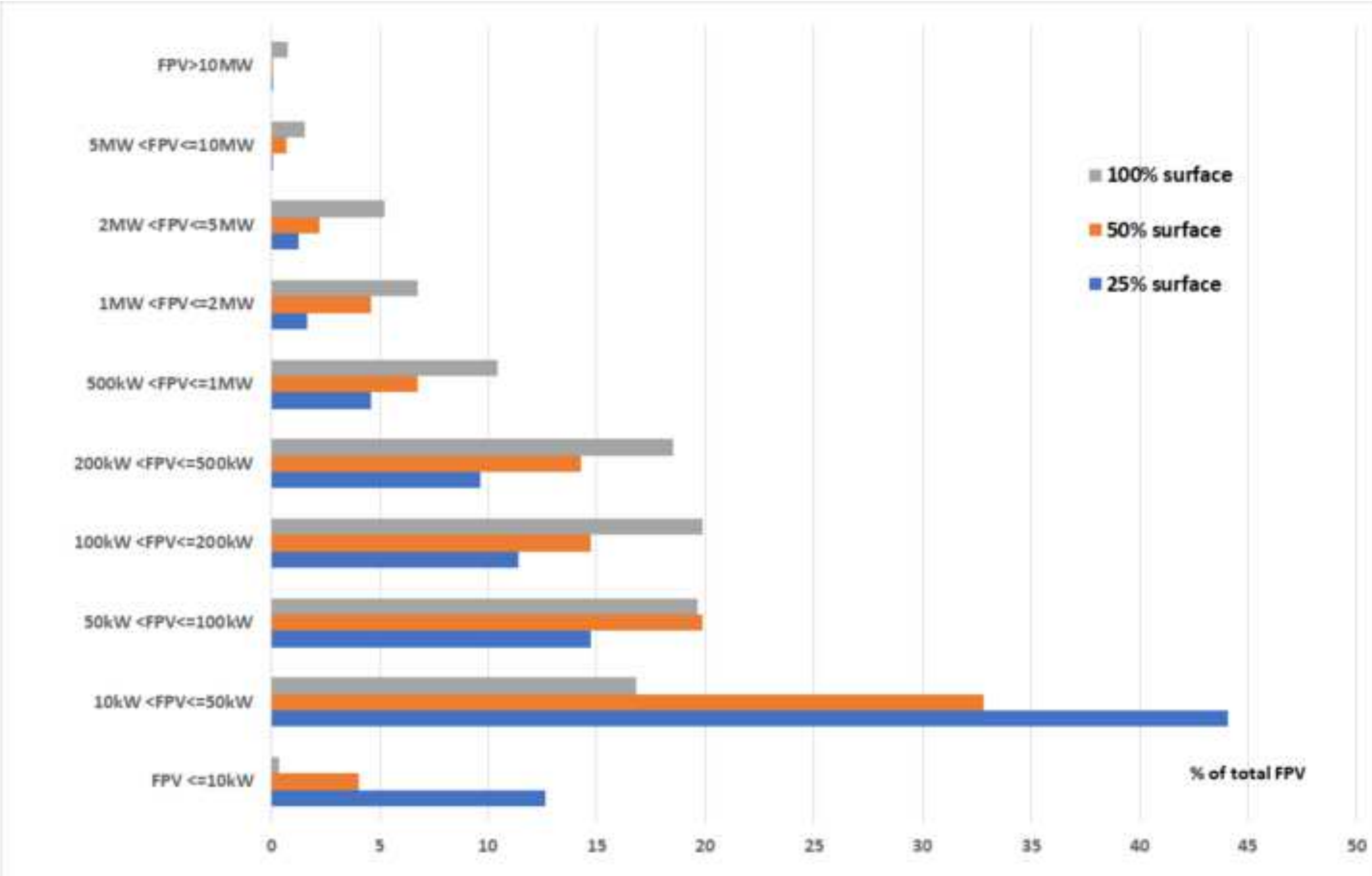

Figure 7

Click here to access/download;Figure;Figure 7.tiff

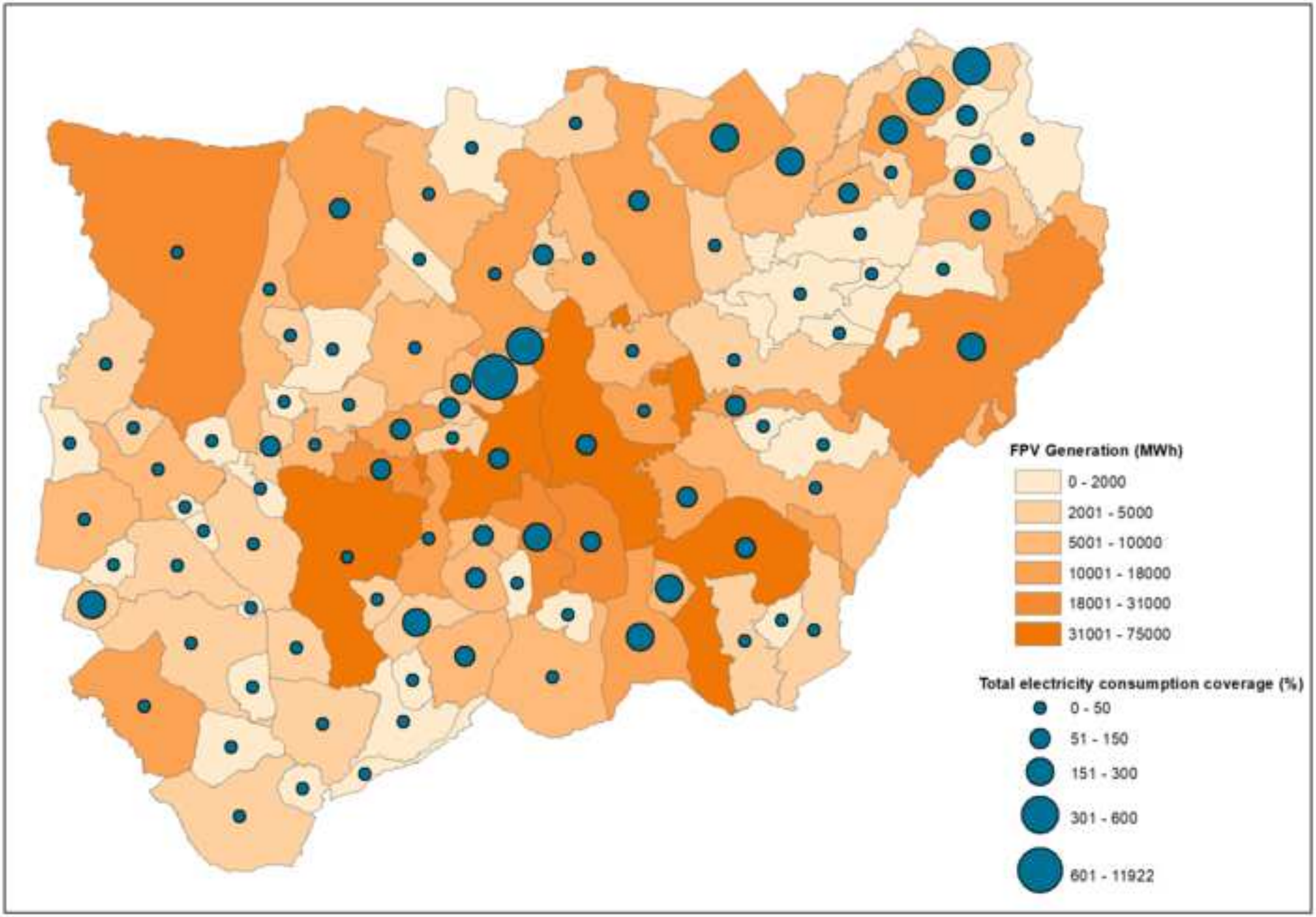

Figure 8

Click here to access/download;Figure;Figure 8.tiff

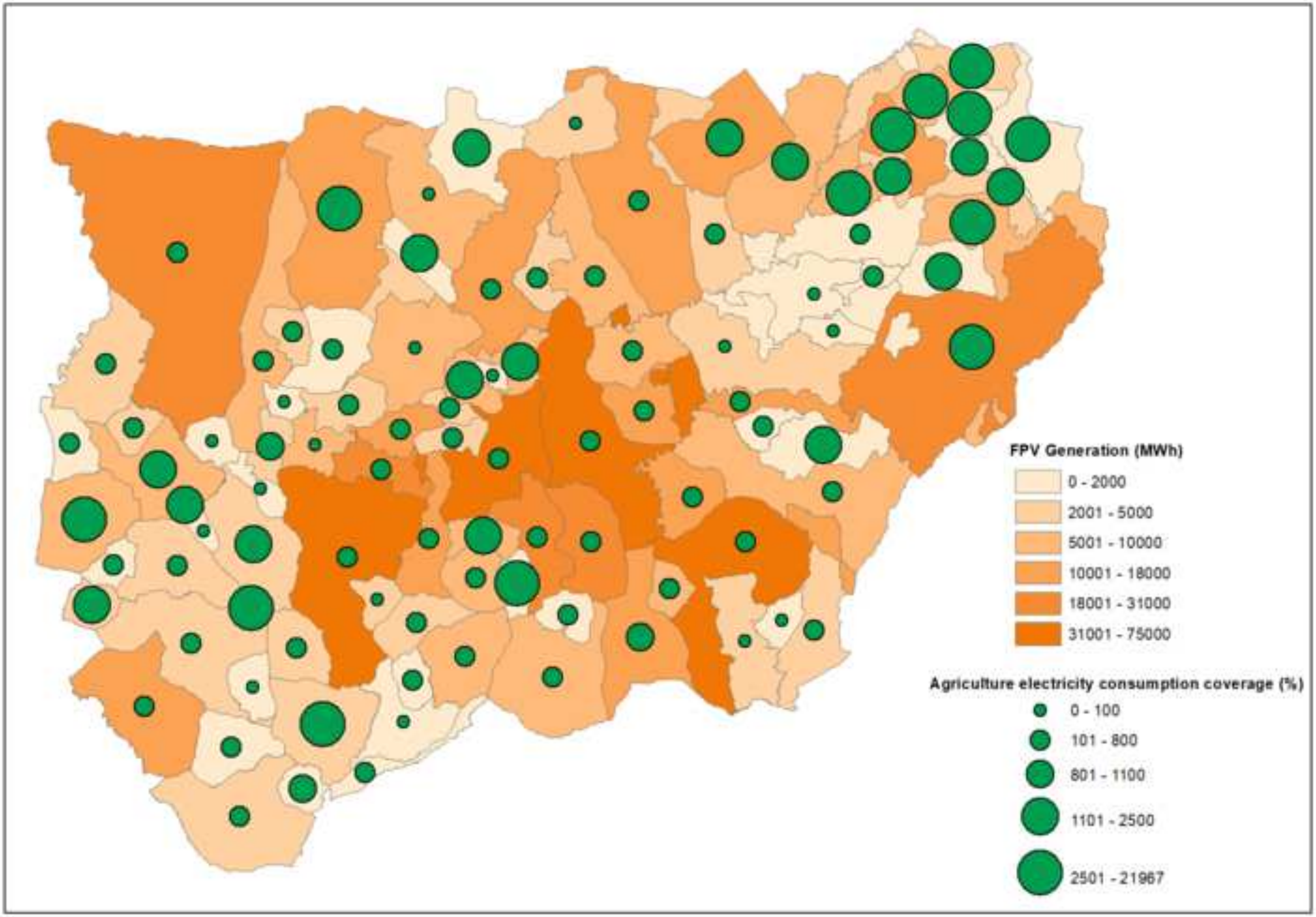

Table 1. Research articles that evaluate FPV technical potential at different territorial scales

Reference	**Scale**	**Natural water body (lakes)**	**Artificial water body**				**Additional reported indicators**	
			Reservoir (power generation)	Reservoir (water supply)	Irrigation pond	Industrial pond	CO_2 emission reduction	Evaporation reduction
Perez et al. [13]	National	x	x					x
Farfan and Breyer [14]	Global		x					x
Tina et al. [15]	Global	x	x	x	x	x		
Kim et al. [3]	National	x	x	x			x	
Château et al. [16]	National					x		
Spencer et al. [17]	National		x	x	x			x
Campos et al. [18]	Sub-national			x				x
Zubair et al. [19]	National	x	x	x				
Stiubiener et al. [20]	National		x					
Micheli [21]	National		x	x	x			
Muhammad et al. [22]	National	x	x	x	x			
Quaranta et al. [23]	Continental		x					
Gonzalez et al. [24]	Continental		x					x
Sulaeman et al. [25]	National		x					
Ravichandran et al. [26]	National		x				x	x
Moraes et al. [27]	Sub-national		x				x	x
López et al. [28]	National	x	x	x			x	
Campos et al. [9]	National		x	x	x	x		

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

	ANDALUSIA (GWh)	**JAEN PROVINCE (GWh)**
AGRICULTURE	1,517.23	289.76
INDUSTRY	8,391.19	669.46
BUSINESS – SERVICES	6,081.36	361.42
RESIDENTIAL	13,198.92	1,079.72
ADMINISTRATION-PUBLIC SERVICES	3,718.21	262.55
OTHER	337.40	21.83
TOTAL	**33,244.31**	**2,684.73**

Table 3. Installed capacity and renewable electricity generation in the province of Jaén by 2020

	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

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

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

Table 5. Electricity generation of the potential FPV systems identified

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

Table 6. Electricity consumption coverage with floating PV systems in the most representative sectors

FPV > 50 kWp	100% Surface	50% Surface	25% Surface
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 %

Table 7. On-ground PV land necessity for the same FPV peak power

	100% Surface	**50% Surface**	**25% Surface**
(no power FPV threshold)	54.48 km^2	27.24 km^2	13.62 km^2
FPV > 10kW	54.48 km^2	27.22 km^2	13.55 km^2
FPV > 50kW	54.05 km^2	26.43 km^2	12.64 km^2

Table 8. On-ground PV land necessity for the same FPV energy generation

	100% Surface	**50% Surface**	**25% Surface**
(no power FPV threshold)	48.92 km^2	24.46 km^2	12.23 km^2
FPV > 10kW	48.92 km^2	24.46 km^2	12.23 km^2
FPV > 50kW	48.53 km^2	24.27 km^2	12.13 km^2

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

Scenario	Avoided emissions ($MtCO_2$/year)	Evaporation reduction (10^6 m^3 / year)	Job creation in C&I (Jobs)	Job creation in O&M (Jobs)
100% FPV	1.14–2.60	35.23	27,482	1,480
50% FPV	0.57–1.30	17.62	13,741	740
25% FPV	0.29–0.65	8.81	6,870	370