Photovoltaic Potential in a City like Elche: Solar Plants and Agriculture.

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Abstract. This article presents a study and analysis of the possibility of generating all the electrical energy we consume as a society through photovoltaic solar energy. A case study is presented, applied to the city of Elche and a portion of its municipal area, also known as "Camp d'Elx." As a first step, it is necessary to determine the region's electrical consumption, as well as the potential for solar generation in the area. In this proposed example, no energy source other than solar has been considered; resources such as wind, hydroelectric, geothermal, or any other type of energy generation have not been taken into account. Only the incident solar irradiation in this region has been analyzed as the primary source of renewable energy. As will be detailed and explained later, generating the electrical energy consumed using photovoltaic solar power installations is initially feasible. However, while it is easy to question this type of analysis from a technical perspective, the article describes how such a solution would indeed be possible.

Keywords: Photovoltaic Solar Installations, Photovoltaic Self-Consumption, Agrivoltaics.

1. Energy Needs and Solar Potential in Elche

Climate change is one of the greatest challenges facing modern societies in the coming years. However, ensuring access to energy while maintaining quality of life and economic development levels are also crucial factors to consider. In this context, it is necessary to address future changes from a perspective of sustainable development. The continuous advancement and development of renewable electricity generation technologies will contribute to achieving these objectives within the energy system. Over the past decade, photovoltaic solar systems have proven to play a significant role as an electricity generation source in most countries. Moreover, when combined with current storage technologies (batteries), which are becoming increasingly affordable, the deployment of these technologies within the electricity generation mix is becoming more favorable. Therefore, a primary conclusion is that maintaining quality of life levels and mitigating climate change requires the development and installation of renewable electricity generation sources to achieve a sustainable energy model. Ultimately, it involves replacing traditional energy generation sources, based on fossil fuel consumption, with more sustainable options such as photovoltaic solar energy. This analysis uses data from a study conducted by a former student of Miguel Hernández University of Elche (UMH), Miguel Parra, in his Bachelor's Project [1]. This project was supervised by professors Demetrio López and Sergio Valero. In this initial study and after consulting various sources of information, such as the Elche PAES for the period 2013-2020, the estimated electrical consumption in the municipality of Elche was approximately 700 GWh/year:

700 GWh/year = 700.000 MWh/year

Clearly, we know that total energy consumption exceeds electrical consumption, but it is necessary to estimate the magnitude of this difference. By comparing local energy expenditure with the national total, we can determine the amount of energy that would need to be generated locally to meet the area's needs. In this context, the total national energy consumption can be obtained from the publication by the Ministry for the Ecological Transition and the Demographic Challenge, "Energy Balance of Spain 1990-2021" [2], which includes the following Sankey diagram:

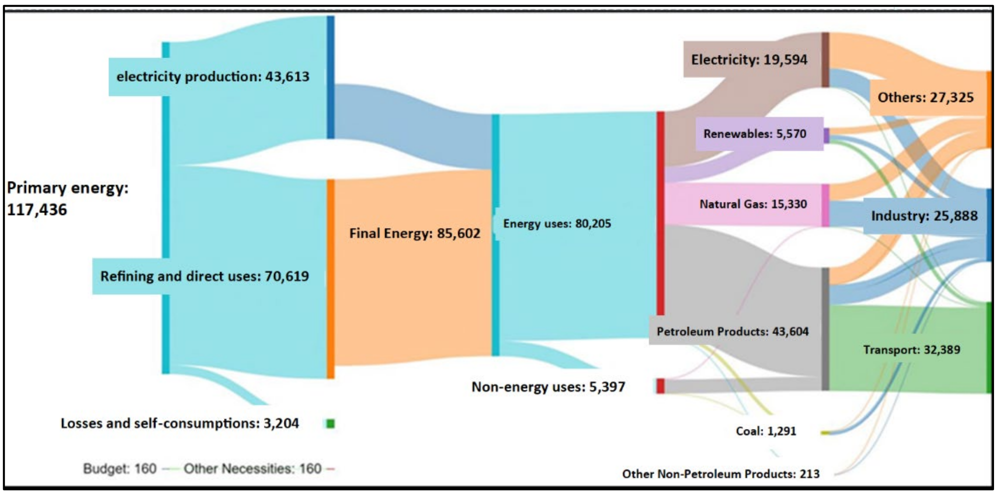


Fig 1. Sankey Diagram of Energy in Spain. Units in ktep.

In the graph, it can be observed that electricity represents approximately one-third of the total primary energy, 43,613 ktep out of a total of 117,436 ktep, which is about 35%. Applying this ratio to a city like Elche would allow us to approximate the total energy expenditure based on its electricity consumption:

700 GWh/year/ 0,35 = **2.000 GWh/year** of total energy.

On the other hand, using the online tool PVGIS (Photovoltaic Geographical Information System) [3] to consult irradiance and solar radiation data, we can estimate the available solar energy in the area. To assess this, we will specifically consider three different types of installations:

1. Photovoltaic installation of the solar park type, with a single-axis tracking system.

2. Photovoltaic installation of the roof type, with some photovoltaic modules oriented towards the "levante" (east) and others towards the "poniente" (west), mounted on the ground.

3. Standardized photovoltaic installation, understood as the most common in the area, in this case for the Elche analysis. However, it should be noted that for this geographical area, an optimized photovoltaic installation would have the best tilt angle and orientation angle to maximize total annual solar radiation capture. This would translate to an approximate tilt angle of 30°-35° and a south orientation angle of 0°. However, for this study, a tilt angle of 20° and an orientation of 30° towards "levante" (southeast) have been considered, as it is a more typical configuration for some rooftops, terraces, or land, and could be the type implemented in "agrivoltaic" installations.

For each of these three installation types, there will be a different land or roof occupancy, from which we will extract the production data per unit area, which we will define as one hectare for ground-mounted installations. Below is the query from the PVGIS database showing the total annual electricity generation (kWh per year) that would be obtained by installing only 1 kW of peak power (in photovoltaic generator field, i.e., in modules) for each of the three installation typologies considered in the study.

Typology 1. Single-axis tracking system. Expected generation: approximately 2,000 kWh/kWp

PVGIS-5, Estimated Values of Solar Electricity Production (Generation)

Provided Data:	Simulation Results
• Latitude/Longitude: 38.265, -0.699	Tilt Angle [°]: 0
• Horizon: Calculated	**Annual PV Output [kWh]: 1977.58**
• Database: PVGIS-SARAH2	Annual Irradiation [kWh/m²]: 2562.32
• PV Technology: Crystalline Silicon	Interannual Variation [kWh]: 48.4
• Installed PV Capacity: 1 kWp	Changes in production due to:
• System Losses: 14%	Incidence Angle [%]: -1.62
	Spectral Effects [%]: 0.41
	Temp. and low irradiance [%]: -9.16
	Total Losses [%]: -22.82

Fig 2. Estimated generation for 1 kWp of installed power in photovoltaic modules, single-axis tracking system.

Typology 2. Roof-mounted system with East/West orientation. Expected generation: approximately 1,350 kWh/kWp

PVGIS-5, Estimated Values of Solar Electricity Production (Generation)

Provided data:	Simulation Results
Latitude/Longitude: 38.265, -0.699	Tilt Angle: 5°
Horizon: Calculated	Azimuth Angle: -90°
Database: PVGIS-SARAH2	**Annual PV Output: 1351.11 kWh**
PV Technology: Crystalline silicon	Annual Irradiation: 1855.45 kWh/m²
Installed PV: 1 kWp	Interannual Variation: 27.32 kWh
System losses: 14%	Changes in production due to:
	Incidence Angle: -3.52%
	Spectral Effects: 0.38%
	Temperature and low irradiance: -12.58%
	Total Losses: -27.18%

Fig 3. Estimated generation for 1 kWp of installed peak power, installation with a 5° tilt and -90° orientation.

Typology 3. Standardized system for installations such as agrivoltaic systems. Expected generation: approximately 1,600 kWh/kWp.

PVGIS-5, Estimated Values of Solar Electricity Production (Generation)

Provided data:	Simulation Results
Latitude/Longitude: 38.265, -0.699	Tilt Angle: 20°
Horizon: Calculated	Azimuth Angle: -30°
Database: PVGIS-SARAH2	**Annual PV Output: 1576.73 kWh**
PV Technology: Crystalline silicon	Annual Irradiation: 2068.77 kWh/m²
Installed PV: 1 kWp	Interannual Variation: 36.99 kWh
System losses: 14%	Changes in production due to:
	Incidence Angle: -2.76%
	Spectral Effects: 0.47%
	Temperature and low irradiance: -9.29%
	Total Losses: -23.78%

Fig 4. Estimated generation for 1 kWp of installed peak power, installation with a 20° tilt and -30° orientation.

The following Table 1 provides a summary, also including the kWp installable per unit area, which we have defined as one hectare:

Table 1. Land Performance by Installation Type.

		kWp per 1 Ha (10,000 m²) Parcel	Annual Production kWh/kWp	Energy Yield of the Land MWh/year
Type 1	Solar Park (Industrial Use)	500	2.000	1.000
Type 2	Bi-directional, Roof and Ground	1.600	1.350	2.160
Type 3	Dual-use (Agrivoltaic)	500	1.600	800

To conduct an economic evaluation of these three potential installation types, it is necessary to understand their installation costs as well as the selling price of the generated energy. This will provide approximate payback periods and assess the feasibility of their potential deployment in the region from an investor/industrial perspective. For estimating sale prices, we rely on historical data, using annual reports from OMIE [4]:

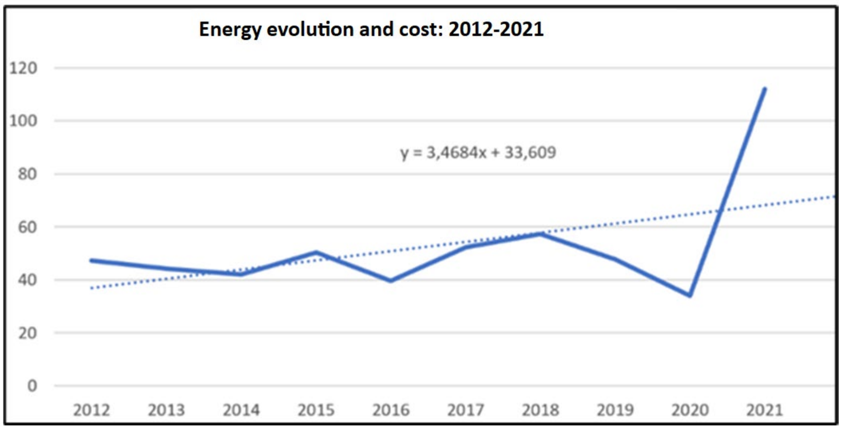


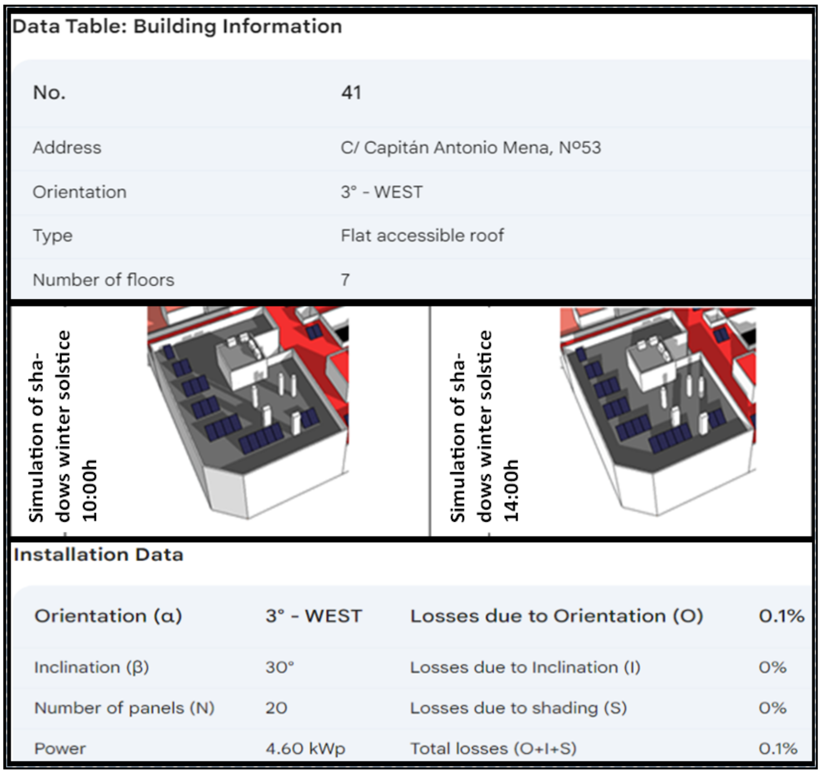
Fig. 5: Historical Energy Costs and Linear Price Increase (3.5% Annual)

From the analysis of historical prices, it can be inferred that the average price for the coming years could approximate €65.00/MWh. Regarding the costs associated with the installation and setup of photovoltaic systems, we can rely on the experience accumulated by Demesol Ingeniería FV to establish different prices for each installation type. Based on these costs and considering the anticipated evolution of electricity prices, it is possible to estimate the future profit from an initial investment, as well as the simple payback period in years. It is also important to note that, although not widely known, there could be opportunities for individual investors to form groups to undertake these installations, thereby sharing the expected returns among all members. This option would be particularly interesting as it would allow residents of Elche to participate in photovoltaic installations through such groups. The following Table 2 summarizes the analyzed data for each considered typology and their performance:

Tabla 2: Energy and Economic Performance by Plant Type

		kWp per 1 Ha (10,000 m^2) Parcel	Energy Yield of the Land MWh/year	Cost €/Wp	Annual Economic Performance	Payback Period (years)
Type 1	Solar Park (Industrial Use)	500	1.000	1,1	65.000,00 €	8,5
Type 2	Bi-directional, Roof and Ground	1.600	2.160	0,7	140.400,00 €	8,0
Type 3	Dual-use (Agrivoltaic)	500	800	1,5	52.000,00 €	14,4

Considering the generation data for the different installation types, it is possible to determine the need for using roofs and land to achieve the necessary renewable and sustainable generation to meet the city's consumption. In an initial analysis, based on the study conducted by a former engineering student in his Bachelor's Project at Miguel Hernández University (UMH) [1], it was estimated that the potential of existing rooftops in the municipality reaches a total installation capacity of approximately 120 MWp. Below are some examples of rooftops:



Data Table: Building Information

No.	41
Address	C/ Capitán Antonio Mena, Nº53
Orientation	3° - WEST
Type	Flat accessible roof
Number of floors	7

Installation Data

Orientation (α)	3° - WEST	Losses due to Orientation (O)	0.1%
Inclination (β)	30°	Losses due to Inclination (I)	0%
Number of panels (N)	20	Losses due to shading (S)	0%
Power	4.60 kWp	Total losses (O+I+S)	0.1%

Fig. 6. Example Data Collection Form for One of the Rooftop Samples.

By aligning rooftops or covers with Typology 2 of generation, it would be estimated that the rooftops in Elche would provide approximately: 120 MWp × 1,350 kWh/kWp/year = 162 GWh/year. This figure would represent about one-quarter, or 25%, of the total electrical consumption. The remaining 75% could be generated using land within the municipality, using Typology 1 installations, which equates to approximately the 540 GWh needed. Additionally, this energy could be obtained through "standardized" photovoltaic installations, which currently have requested construction permits, requiring a total of 270 MWp of installed capacity. According to the data in Table 1, the land needed to obtain this energy would be approximately 270 hectares, which represents, given that the municipal area of Elche covers a total of 326 km², a percentage not exceeding 2%, approximately 1.7%. As a preliminary conclusion, it would indeed be possible to meet the city's electrical needs by utilizing all available rooftops as well as less than 2% of the Camp d'Elx land. However, this analysis aims to cover all energy needs, not just electrical ones, particularly by electrifying other sectors (with electric vehicles being a clear example of the transition from fossil fuels to electricity). Considering the estimated total annual energy consumption of 2,000 GWh/year, the following Table shows the results obtained for covering this consumption with photovoltaic solar installations:

Tabla 3: Generation and Land Use

	MWp	GWh/año	Land Use in Hectares (% of Municipality)	% Energy
Rooftop Utilization (Type 2)	120	162	0 (0%)	8%
Land Utilization (Type 1)	919	1.838	1.838 (5,6%)	92%

In summary, it is possible to meet the city's energy needs by utilizing all rooftops and approximately 6% of the municipal land. At this point, it is crucial to highlight that these theoretical calculations provide an idea of what it would entail to transition from a generation system primarily based on the use and consumption of fossil fuels to one based on renewable energy sources. However, realistically, it is not as straightforward as the numbers suggest. There are at least two major obstacles to consider, which represent significant challenges requiring analysis and study to achieve the goal of near-zero emissions. These two major challenges are:

The capacity of the Electrical Networks. It is essential to analyze whether the networks are prepared to absorb both the new generation capacity that will be required and to supply all the new electrical demands, such as the increasing incorporation of electric vehicles into the fleet. Online data indicates that the current network capacity in the area is significantly lower than what would be needed according to the analyses conducted in this study. The following figure shows a snapshot of the I-DE network capacity map consulted in October 2023 [5].

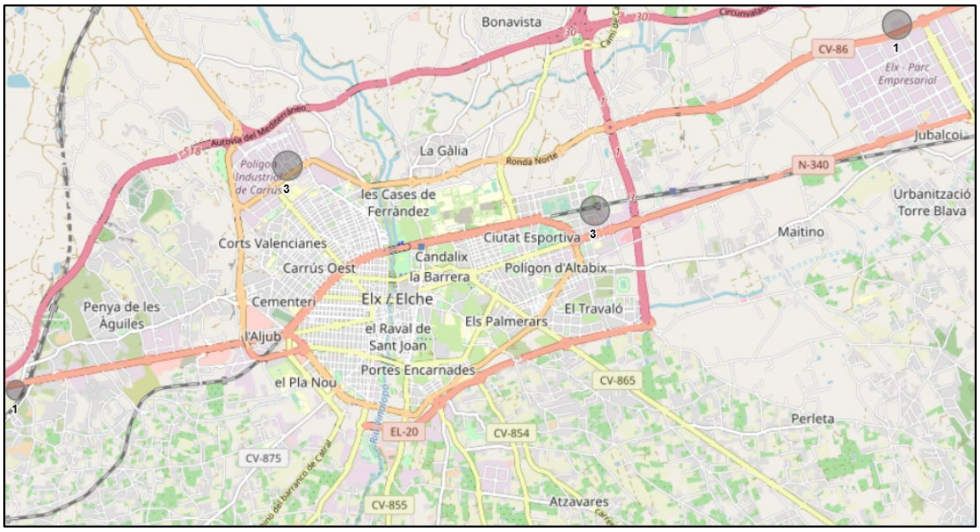


Fig. 7: I-DE Capacity Map [5] as of October 2023, approximately 8 MW

1. Consumption does not always align with generation. In the case of photovoltaic installations, this alignment occurs only during certain hours of the day. That is, there is a significant disparity between generation and consumption. It is evident that with photovoltaic power generation, nighttime use is not possible when there is no sunlight. For example, Figure 8 shows a comparison between the electrical

generation curve of a photovoltaic installation and a typical electrical demand or consumption curve.

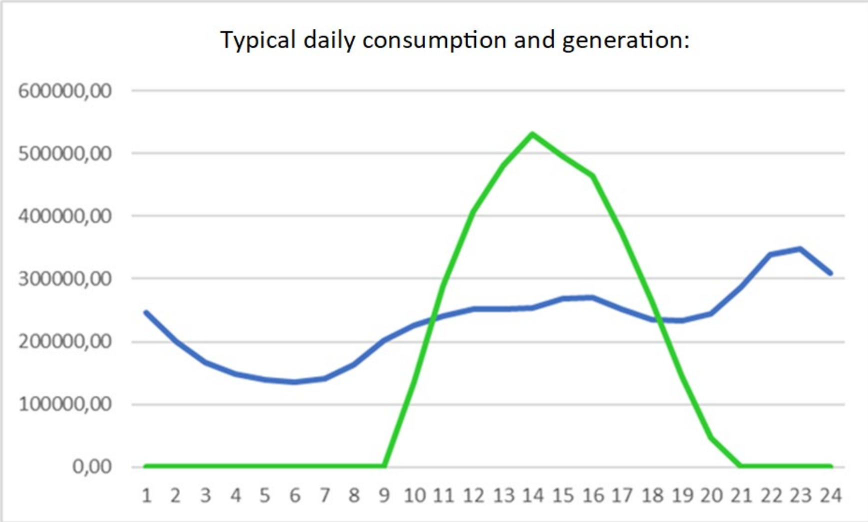


Fig. 8: Consumption Curve vs. Generation Curve on a Typical Day. Green curve represents generation, and blue curve represents consumption [6].

A significant portion of these two challenges could be addressed through the use of storage systems (primarily batteries, though not as the sole solution), which would reduce the dependency on the networks and allow for a more seamless match between generation and demand. Therefore, the analysis of these two issues and their potential solutions remains pending and will be addressed in future research efforts. These topics are included in the research objectives of the newly established "Demesol Chair of Photovoltaic Solar Energy" at UMH.

2. Solar Plants vs. Agriculture and Conservation of the Camp d'Elx

As described in the previous sections, it is possible to meet the overall energy needs of a city like Elche through the installation of photovoltaic solar power systems [7], utilizing both rooftop surfaces and available land. However, this is precisely where new challenges arise related to establishing and installing solar plants on land. For example, in some cases, opposition to land-based solar installations is based on arguments concerning proximity to rural homes, landscape impact, biodiversity, agricultural mosaic, etc…[8]. It is clear from such arguments that solar installations are often perceived as conflicting with the established uses in the Camp d'Elx area. To illustrate this perspective, consider the shift from the landscape shown in Figure 9 to the view depicted in Figure 10:

Fig. 9: Example of a “typical” view of some areas in the Camp d’Elx.

Fig. 10: Example of a “typical” view of a photovoltaic solar installation on rural land.

Thus, opposition to the use of land often makes it challenging to advance the proposed model, even when there is an opportunity to generate all the energy consumed within the territory.

3. A Possible Solution: Agrovoltaics

Below is a solution approach that would enable the compatibility of photovoltaic solar installations with traditional agricultural use. This means utilizing the land for dual purposes—combining photovoltaic performance with agricultural productivity—allowing landowners to continue their agricultural activities while also earning additional income from solar energy generation. However, this approach has the drawback of typically yielding lower performance compared to standardized typologies (see previous sections), and it involves higher costs. These factors may reduce its appeal to investors unless a more specialized analysis is conducted based on each specific case, location, and technical conditions of the installation. This leads to the conclusion that further studies are needed to develop viable installations for both plant promoters (investors) and local residents and/or farmers in the Camp d’Elx area. Lastly, we summarize the main features of "Agrovoltaics," based on a study conducted by the Fraunhofer Institute [9]: Agrovoltaics allows for the simultaneous development of agriculture and photovoltaics on the same land, a key combination in the energy transition.

Fig. 11: Example of a Typical Agrovoltaic Installation.

Agrovoltaics can significantly increase the economic value of land used for cultivation, leading to several additional benefits:

- Creation of More Jobs in Rural Areas: Agrovoltaic systems can stimulate local economies by creating new job opportunities in rural communities.
- Protection of Crops from Extreme Weather Conditions: The installation of solar panels can shield crops from harsh weather, potentially reducing crop damage.
- Increased Biodiversity and Local Food Production: Agrovoltaics can support local ecosystems and increase the diversity of species while boosting food production.

Agrovoltaic systems enable farmers to continue their agricultural activities while minimizing environmental impact. The installation of solar panels on farmland offers new sources of income without interfering with farming. Some potential advantages include:

1. Protection Against High Temperatures and Extreme Weather: Higher temperatures increase water consumption and hinder crop growth. Modern photovoltaic module technology allows for adjustment of sunlight exposure, helping to reduce temperatures, protect against wind, and decrease soil erosion.

2. Reduction of Evaporation and Increased Soil Moisture: The shade provided by solar panels can reduce evaporation, saving a significant amount of water, increasing soil moisture, and maintaining optimal water levels for plants. Additionally, panels can be used to collect rainwater, conserving groundwater.

3. Improvement of the Ecosystem: Agrovoltaics contribute to sustainable development and the protection and enhancement of biodiversity without changing land use. For instance, they can support beekeeping and livestock farming and allow for vegetated fencing around the installation.

4. Increased Electricity Production, Efficiency, and Economic Value: Crops grown under solar panels can help lower temperatures and increase productivity. It is estimated that photovoltaic electricity generation can boost economic value by over 30% due to improved land and production efficiency, especially in warm climates like Elche.

5. Additional Income and Greater Security Against Crop Losses: The energy produced by the photovoltaic installation can be sold to the grid, stored, or used for production needs such as lighting and irrigation.

However, there are also some disadvantages:

- Higher Investment Costs: The cost of agrovoltaic systems tends to be higher than that of standard ground-mounted solar parks, primarily due to the use of more complex structures and the potential need for bifacial modules.

- Lower Photovoltaic Efficiency: Compared to standard solar parks, agrovoltaic systems may have lower efficiency because some sunlight must be allowed to reach the crops.

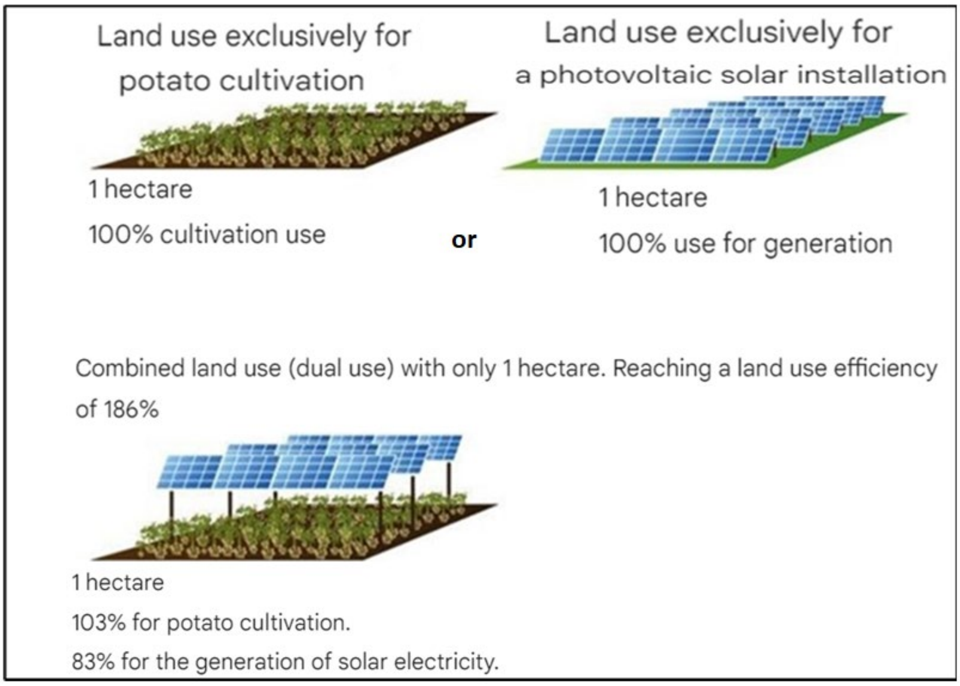


Fig. 12: Example of Agrivoltaic utilization in potato cultivation

Another important classification of Agrivoltaic Installations would be into these three types.

Type 1: Agrovoltaics through conventional (standardized) photovoltaic solar plant installations.

In this case, livestock and plant crops for grazing, as well as beekeeping and/or livestock farming operations, are integrated within the solar plant itself and between the rows of photovoltaic modules. This setup enhances animal welfare by providing additional shade and protection from the wind through the modules. Figure 13 shows an image of this type of installation.

Fig. 13: Inclusion of nursery vegetation between rows of modules.

Type 2. Elevated Photovoltaic Panels.

In this type of installation, photovoltaic modules are placed at a higher-than-usual elevation, between 2.5 and 5 meters above the ground, depending on agricultural needs. This configuration allows for the passage of people and even the use of certain types of machinery for harvesting. It is ideal for larger crops and harvests, such as fruit trees or vineyards. The spacing between the rows of modules and the ground, as well as between the panels themselves, allows sunlight to reach the crops without hindering their growth. Another advantage of this solution is a reduced dependence on single-use plastics, as the panels can provide up to 30 years of protection, which is the estimated lifespan of a photovoltaic plant. Figure 14 shows an example of an elevated solar structure.

Fig, 14: Example of an elevated solar structure.

Type 3. Greenhouses and Nurseries.

In this case, photovoltaic modules are integrated into the roof of a nursery or greenhouse, enabling the sustainable generation of renewable electricity without reducing crop yield. It is necessary to verify the technical criteria and urban planning requirements since solar greenhouses are not classified as "buildings." Therefore, photovoltaic modules integrated into their roofs, besides being an integral part of the structure itself, do not constitute "building-integrated photovoltaic systems." It is important to consider that a greenhouse typically consumes significant energy to maintain optimal temperatures, lighting, and critical processes that make it effective. In this regard, technology exists to optimize the tilt and orientation of photovoltaic modules according to the season or months when, for instance, greater ventilation inside the nursery is required. Figure 15 shows an example of a photovoltaic solar installation integrated into a greenhouse structure.

Fig. 15: Example of a photovoltaic solar installation on a greenhouse roof.

4. Conclusions

From the analysis of consumption and photovoltaic generation possibilities in the population of Elche, it can be concluded that it is feasible to supply, if not all, a significant percentage of the energy demand. It is also possible to generate a substantial portion of the consumed energy within the same area by leveraging high solar irradiation levels and available land. On the other hand, besides the two main technical challenges—network capacity availability and the alignment between generation and consumption—a third obstacle is the opposition in many cases to using agricultural land for photovoltaic purposes. However, this latter challenge can be overcome through the use of "Agrivoltaics," which allows for dual use of the same land, maintaining its agricultural productivity while simultaneously enabling renewable, sustainable, efficient, and long-lasting electricity generation over several decades. Nevertheless, potential additional costs and uncertainty regarding acceptance by the most critical and skeptical parties make it difficult to predict its short-term evolution. Finally, it is concluded that much more research and studies are needed to reach a clear and feasible definition of this photovoltaic solar potential, where Agrivoltaics will play a key and decisive role in overcoming resistance from certain sectors to the use of photovoltaic installations on land.

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