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Using solar energy for irrigation in large water distribution networks: A benchmark study about six irrigation systems in the south of Spain

Maaike van de Loo *, Emilio Camacho Poyato, Juan Antonio Rodríguez Díaz

Department of Agronomy, University of Córdoba, Campus Rabanales, 14072 Córdoba, Spain

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A B S T R A C T

Increased energy requirements and rising energy costs have led to a growing adoption of solar energy in large irrigation systems, especially in southern Spain. This benchmark study evaluates six large-scale irrigation systems, assessing solar energy integration and its interplay with agricultural water management practices. Results indicate that while the ratio of solar energy to total energy consumption ranges from 0.40 to 0.57 across systems with large solar plants of several MWs, full solar energy utilization remains constrained due to the 24-h on-demand irrigation schedules, necessitating reliance on conventional energy during non-solar hours. Despite reductions in energy consumption, in most systems energy costs rose significantly, with increases between 15 % and 302 %, driven by global market fluctuations. Selling excess solar energy presents a potential economic relief, yet regulatory restrictions often inhibit this practice. Even when feasible, profitability is challenged by dynamic energy prices. The study highlights the need for innovative solutions, including energy storage technologies like batteries and pumped hydropower, and systemic scheduling adjustments to enhance solar energy use. Broader adoption of technologies such as floating solar panels and certifications like ECO20 could further support energy sovereignty and sustainability. This research underscores the challenges and opportunities in optimizing solar energy for irrigation, offering valuable insights for system managers and policymakers navigating the transition to renewable energy in agriculture.

1. Introduction

In recent years, the energy requirements of irrigation systems have increased significantly due to the switch from surface irrigation to pressurized irrigation systems like sprinkler and drip systems [1–3]. To cope with these higher energy requirements and associated costs, irrigation systems are currently starting to use solar energy as an alternative energy source. The use of photovoltaic solar energy for irrigation is therefore now rising in popularity in large water distribution networks. However, despite the fact that solar energy is a more sustainable alternative for fossil fuels, still challenges arise while using solar energy in large irrigation systems. One challenge is matching the production of solar energy with the irrigation demand, as many networks are organized on-demand while solar energy can only be produced during daylight hours [4,5]. Given the increase in the use of solar energy in large irrigation systems in the south of Spain over the past five years, this paper examines its application in these systems.

With the growing global population and increasing food demand, sustainable intensification of irrigated agriculture has become crucial. Irrigated agriculture accounts for 70 % of global freshwater withdrawals and contributes approximately 40 % of global food output, despite covering only 24 % of croplands [6], showing the importance of irrigated agriculture in meeting global food demands. Compared to rainfed agriculture, irrigation offers significant advantages for farmers, such as securing crop production, improving product quality, and enabling the cultivation of summer crops otherwise unfeasible in rainfed conditions [7]. These benefits have driven the expansion of irrigation, albeit increasing pressure on water resources. To enhance water use efficiency and thereby reduce the pressure on water resources, many regions are transitioning from traditional surface irrigation systems to more advanced pressurized systems, such as sprinkler and drip irrigation [8–10]. While these modern methods enable more precise water distribution, they also have the unintended consequence of significantly increasing the energy requirements of irrigation systems, which in turn raises energy costs.

A country where energy requirements for irrigation have particularly increased in recent decades is Spain. Between 2002 and 2015, the country undertook an intense irrigation modernization, aiming to

* Corresponding author.
E-mail address: maaikevandeloo@uco.es (M. van de Loo).

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achieve required water savings in the agricultural sector. This modernization project included lining old canals and replacing open channel distribution networks with on-demand pressurized networks. The irrigation systems in Spain have thereby undergone a shift: while they previously used relatively large amounts of water and minimal energy, they now theoretically require less water but demand significantly more energy. Besides, rising energy prices in recent years have made energy consumption a major contributor to irrigation operating costs. Rodríguez Díaz et al. [11] argue that in some cases, modernizing irrigation systems, instead of benefiting farmers, creates challenges when energy demands become excessively high. This issue is exacerbated by increasing costs of energy from conventional sources. As a result, farmers, who traditionally faced the challenge of water scarcity, now must also contend with the consequences of adapting their systems to address water shortages, namely, increased energy demands and costs. These dual pressures—water scarcity and higher energy expenses—threaten the economic viability of farming.

Increasing energy consumption for irrigation not only raises energy costs but also results in higher greenhouse gas emissions. Agricultural systems still largely depend on fossil fuels, which contribute to global warming and are limited resources [12]. To tackle climate change, the European Green Deal aims to increase the share of energy derived from renewable sources, such as wind and solar, to 40 % by 2030 and reach climate neutrality by 2050 [13]. Spain, benefiting from abundant solar radiation, has historically underutilized its solar energy potential, but recent policy changes, like the removal of the solar tax in 2019, have spurred growth in solar capacity [14,15].

The use of solar energy for powering irrigation systems is increasingly gaining popularity in the agricultural sector as a way to reduce energy costs and decrease greenhouse gas emissions. Initially, solar energy was applied mainly in small irrigation systems at farm level, just to supply water to the on-farm irrigation systems, in places where no other energy sources were available [16]. Many studies have already analysed or designed such standalone, solar-powered irrigation systems, showing their feasibility in remote locations where electricity is not available or difficult to obtain [17–21]. In these areas, the use of solar energy can be a technically, economically and environmentally feasible alternative to turn rainfed fields into irrigated ones: it has low operational and maintenance costs, it is a sustainable source of energy, and it makes irrigation possible in off-grid areas, which enhances the crop production.

More recently, solar energy has also started to be used in large irrigation schemes where the pressurized irrigation networks require large amounts of energy for their operation. These irrigation schemes do not use standalone solar-powered systems, as is the case in small irrigation systems or off-grid areas, but rather a combination of solar energy and conventional energy from the grid. In these systems, solar energy is seen as an alternative to deal with rising energy costs, while at the same time offering a sustainable path for the phasing out of fossil fuels [2,22,23]. Nevertheless, the use of solar energy for irrigation in large water distribution networks also presents several challenges. One of these challenges is matching the produced solar energy with the irrigation demand. In large irrigation systems, irrigation is delivered on-demand: water is continuously available to farmers, including at night. In the case of using conventional energy, energy is generated when demanded and the supply of energy is therefore matched with the demand. However, when using renewable energy, generating energy depends on the availability of the resource. Instead of having energy being supplied constantly, the energy supply is intermittent and depends on meteorological conditions [23–25]. While solar and wind, for example, are important sources for the production of energy, the intermittency of the resources is still a challenge while matching the energy production with the energy demand [4,5,26].

The challenge of matching the produced solar energy with the irrigation demand has already been studied in detail for the Valle Inferior irrigation system, located in the south of Spain [4]. The Valle Inferior system started using solar energy in 2019 to meet the growing demand for energy without having an increase of the energy costs. The irrigation system installed a solar plant with a power of 6 MWp to supply water to their approximately 19,000 ha, in a hybrid system that combines both solar and conventional energy [4]. In 2021, although the solar plant of the Valle Inferior system produced more energy than the total annual energy consumption of the irrigation system, only 54 % of the total energy consumption was provided by the produced solar energy; in 2022 this was 57 %. The fact that still a large part of the energy consumed for irrigation is coming from conventional energy is mainly the result of continuous night-time operation. The energy consumption of the irrigation system is relatively constant throughout the day and night, which makes that about half of the energy is consumed during the day, when solar energy can be produced, while the other half is consumed during the night, when conventional energy is required.

While defining the optimization strategy for solar energy use in the Valle Inferior system, van de Loo et al. [4] studied two scenarios. The first scenario aimed to optimize the use of own-produced solar energy by adjusting the 24-h irrigation schedule to schedules of 8 or 12 h. It was found that adjusting the irrigation schedule to irrigation during the day increases the use of solar energy significantly—up to annual percentages of 98 %—depending on the water availability in the area and the length of the irrigation schedule. However, during interviews with several farmers in the Valle Inferior system, the farmers mentioned that they prefer to irrigate during the night instead of during the day to minimize their water losses through evaporation, especially in dry years. Furthermore, farmers are sometimes still used to the lower energy prices during the night, while due to the excess of renewable energy generation, in Spain, and in many other countries, the energy prices are now lower during the day [27]. The second scenario aimed to optimize the economic profits of selling excess solar energy. In this case, changing to irrigation during the day was not always the most beneficial. In years with a higher water availability, and therefore a higher energy consumption, it was more beneficial to maintain a 24-h schedule. This was due to the influence of the energy tariff schedules at the time of the study, with lower energy prices during the night. Besides water availability and irrigation schedule, the optimum of the second scenario thus also depends on these dynamic energy prices.

Van de Loo et al.'s [4] study showed that, although solar energy is a sustainable alternative for fossil fuels, still challenges arise while implementing it in large irrigation networks. The results demonstrate that the outcomes for the two scenarios differ under differing assumptions for the key variables, which leads to new challenges in the management of irrigation systems. The operational strategy chosen by an irrigation system, either optimizing the use of own solar energy or optimizing economic benefits from selling solar energy, depends on various variables which can differ from year to year. Using solar energy in large irrigation networks therefore adds another operational concern. Besides dealing with low water availabilities, irrigation systems now must also deal with the (changing) management of energy consumption and solar energy production, in order to maintain irrigation that is both efficient and economically viable.

The Valle Inferior system has been one of the first large water distribution networks in Spain that started using solar energy for irrigation. Since then, several other large irrigation systems in the south of Spain have followed. The case of the Valle Inferior irrigation system showed that there is still room for optimization when using the produced solar energy. For this reason, this paper continues on the previous research by examining whether other large irrigation systems face similar challenges as the Valle Inferior system. This is done by performing a benchmark study on the use of solar energy in six large irrigation systems—with different characteristics (size, crops, irrigation methods, capacity of solar plant)—located in the south of Spain. This study, therefore, aims to assess the performance of irrigation systems that have already integrated solar energy by benchmarking these systems. It also seeks to broaden the understanding of matching produced solar energy with irrigation demand in large water distribution networks, while examining whether different agricultural water management practices influence the performance of solar energy in these networks. These findings could be valuable for managers of large irrigation systems and policy makers, providing insights into maximizing solar energy use and aligning it more efficiently with irrigation demands, in Spain and elsewhere in the world.

The rest of the article is structured as follows: Section 2 provides an overview of benchmark studies and explains the methodology used in this research. Section 3 includes information on the study area. Section 4 presents the results and discusses these findings, particularly focusing on agricultural water management practices observed across the six irrigation systems. Section 5 expands the discussion by addressing broader implications and challenges associated with the integration of solar energy in large-scale irrigation systems. Section 6 presents the recommendations, and finally, Section 7 ends with the conclusions.

2. Methodology

2.1. Benchmark study

The comparative analysis of the irrigation systems has been done by benchmarking. Benchmarking is defined as *"a systematic process for securing continual improvement through comparison with relevant and achievable internal or external norms and standards"* [28]. In the agricultural sector, the objective of benchmarking is to improve the performance of an irrigation system. This is done by determining which practices lead to better performance of a system and adapting these practices in irrigation systems that perform less efficiently. In order to compare different irrigation systems, performance indicators are identified that describe the main characteristics of each system [28]. Making use of performance indicators allows that a large amount of information can be simplified to a single number, which makes it easier to compare different irrigation systems with each other. The performance indicators used in this study are discussed in Section 2.3.

Benchmarking techniques have already widely been used in the agricultural sector to evaluate and compare the performance of irrigation systems. Molden et al. [29] defined various external and comparative performance indicators, such as the output per cropped area, relative water supply, relative irrigation supply and gross return on investment, to compare irrigated land and water use in irrigation systems. Burt and Styles [30] used these existing indicators in their study to examine the performance of 16 irrigation projects and furthermore recommended several new indicators, such as an indicator that demonstrates the difference in production with or without irrigation. These two studies mainly focussed on irrigation performance in developing countries, where it was found that making use of indicators is an effective tool to compare the performance before and after changes in an irrigation project.

Alexander and Potter [31] also started evaluating the use of benchmarking in developed countries, by focussing on Australian irrigation systems. It was concluded that benchmarking achieves a better understanding of the performance of Australia's irrigation sector and, furthermore, that it provides recommendations for improving the sector in the future. In Spain, Rodríguez-Díaz et al. [32] have been one of the first to use benchmarking to compare water use efficiency in irrigation systems, by analysing performance indicators in nine systems in Andalusia, Spain. This study marked benchmarking as a powerful tool to evaluate the efficiency of irrigation systems.

The above mentioned studies all focused on evaluating irrigation performance, but mainly concentrated on water use and not on other important resources in the agricultural sector, such as energy. Many studies have emphasized the importance of analysing both water and energy efficiency in irrigation systems, as these two resources—water and energy—are interlinked to each other and cannot be considered independently [33–35]. For this reason, instead of only analysing the water use performance, the Spanish Institute for Diversification and Energy Savings (IDEA) started to examine various energy indicators [36]. Furthermore, Rodríguez Díaz et al. [7] carried out a benchmark study about water and energy use in ten pressurized irrigation systems in Andalucia, Spain, and Fernández García et al. [37] used performance indicators to compare both water use and energy consumption before and after irrigation modernization in Spain.

Benchmarking thus has proved to be an effective tool to evaluate the performance of water use and energy consumption in irrigation systems. Until now, when analysing the energy consumption, only the conventional energy consumption has been examined. There are, to our knowledge, no previous studies that benchmark the use of solar energy in irrigation systems. However, the recent phenomenon of using solar energy for irrigation is gaining popularity in large irrigation networks. Therefore, this study uses benchmarking to compare the use of solar energy in large water distribution networks, focussing on irrigation systems located in the south of Spain. The increase of the energy requirements of irrigation systems, together with the rising energy prices, makes that optimal use of the produced solar energy will be essential for these systems to deal with the increasing energy costs for irrigation. Evaluating the current solar energy management, by making use of benchmarking techniques, contributes to better performance of the use of solar energy in irrigation systems that already use solar energy and in irrigation systems that want to implement it in the future, in Spain and elsewhere.

2.2. Methodology

2.2.1. Selecting irrigation systems

The six irrigation systems selected for this study are located in southern Spain, specifically in the regions of Andalusia and Extremadura. These areas were chosen due to their significant agricultural activity, their reliance on irrigation due to the predominantly dry climate, and their increasing integration of solar energy in irrigation systems. The integration of solar energy into large irrigation systems is a recent phenomenon that has not been extensively studied. Therefore, by benchmarking these systems, this study aims to assess the performance of irrigation systems that have already integrated solar energy, and to examine whether different agricultural water management practices influence the performance of solar energy in these networks.

Several agricultural water management practices were considered to evaluate the performance of the irrigation systems. The following key practices were taken into account: irrigation method, irrigation schedule, deficit irrigation practices, and crop type. These water management practices are important as they directly influence the efficiency of both water use and energy consumption in irrigation systems. By comparing these practices across different systems, the contribution of each practice to the overall performance of the system, particularly in terms of the integration of solar energy, is assessed.

Importantly, while these systems are geographically located in southern Spain, their characteristics make them representative of large irrigation systems worldwide that integrate or want to integrate solar energy. The insights gained from this research are applicable to other regions with similar conditions, since the underlying challenges and opportunities of solar energy adoption in irrigation are not specific to their geographic location but rather to the on-demand operation of irrigation, and the scale and energy requirements of the systems. This enhances the relevance of the findings for global agricultural water management.

2.2.2. Defining performance indicators

While selecting the irrigation systems, performance indicators were defined to facilitate a comparison between the different systems. These indicators are required for assessing the performance of irrigation systems in terms of water use, energy consumption, and financial costs. The indicators are divided into three categories:

- Water use indicators: These assess how efficiently water is used in the irrigation process.
- Energy indicators: These include both general energy consumption and specific indicators for solar energy use.
- Financial indicators: These provide insight into the economic implications of using solar energy, including costs and cost reductions.

These indicators encompass measurable variables of the irrigation systems, either considered independently or in relation to one another. Their selection is crucial to the success of the benchmarking process, as they make it possible to distinguish differences between irrigation systems and identify which are the most efficient. A detailed explanation of the specific indicators can be found in Section 2.3.

2.2.3. *Field visits and data collection*

After selecting the systems and defining the performance indicators, field visits were conducted to the six irrigation systems. During these visits, interviews were held with technical staff, and the solar plants were visited. These activities provided a better understanding of the study area and offered general information about the systems, such as their size, irrigation methods, types of crops, and the power of the solar plants. These findings are presented in Section 3, Study area.

Following the field visits, more specific data were requested from the technical staff. The provided datasets included detailed records on irrigation water volumes, energy consumption, solar energy production and consumption, and operational costs. These data were required for calculating the performance indicators and understanding the operational context of each system. The data covered the years 2021 and 2022, which form the temporal scope of this research, as these years represent the first complete operational periods for the solar plants in most of the systems.

2.2.4. *Data analysis and discussion*

Once the data were collected, the performance indicators were calculated for each irrigation system. The analysis focused on indicators related to water use, (solar) energy consumption, and costs. The results of these calculations, along with an initial discussion to clarify and interpret the findings, are presented in Section 4, Results. Including this discussion in the results section allows for a clearer and more immediate understanding of the findings. Section 5, Discussion, provides a more comprehensive analysis, exploring the factors that may explain the observed variations and discussing the broader implications of the results for the future use of solar energy in large irrigation systems.

2.3. *Performance indicators*

2.3.1. *Water use indicators*

The water use indicators have been defined to compare the irrigation water use in the different systems. These indicators give insight in how much water is actually available for irrigation, how much water is required to irrigate the crops, and to what extent these requirements are being met. The indicators are partly based on Malano and Burton [28]. The following indicators have been defined:

1. The assigned water allocation [m^3 ha^{-1}] is the maximum volume of water that farmers are allowed to use for irrigation. This water volume is assigned by the water authority in the area and is allocated per irrigation season, which runs from March/April to the end of September (depending on rainfall and the volume of water stored in the basins).
2. The annual irrigation water supply [m^3] is the total volume of water pumped for irrigation in the corresponding year.
3. The irrigation supply per hectare [m^3 ha^{-1}] is calculated by using Eq. (1), showing the volume of water applied per hectare of land. This indicator may vary between areas within the irrigation system, based on specific agricultural water management practices and environmental conditions.

$$\text{irrigation supply per hectare}\left[\mathrm{m^3\ ha^{-1}}\right] = \frac{\text{annual irrigation water supply}\left[\mathrm{m^3}\right]}{\text{total area irrigation system}\left[\mathrm{ha}\right]} \quad (1)$$

4. The effective rainfall [m^3] is the difference between the total rainfall and the actual evapotranspiration. For the irrigation systems located in Andalusia, both the monthly rainfall and evapotranspiration have been obtained from data of the Andalusian Agroclimatic Information Network (*Red de Información Agroclimática de Andalucía*). Afterwards, the annual effective rainfall is calculated by entering the obtained data in Cropwat. In the case of a system located in Extremadura, the data are directly obtained from the Agroclimatic Information System for Irrigation (*Sistema de Información Agroclimática para el Regadío)*.
5. The annual irrigation water requirements [m^3] indicate the amount of water that is needed to apply to a crop to fully meet the crop water requirements in addition to water supplied through effective rainfall [38]. These requirements have been calculated by using Cropwat. To simplify the cropping pattern, only crops that cover 2 % or more of the total area of the irrigation system have been used, as crops that cover less than 2 % will not make a significant difference on the total irrigation water requirements. The requirements are calculated for the irrigated area.
6. The relative irrigation supply (RIS) [−] is the ratio between the annual irrigation water supply [m^3] and the annual irrigation water requirements [m^3] (Eq. (2)).

$$\mathrm{RIS}\left[-\right] = \frac{\text{annual irrigation water supply}\left[\mathrm{m^3}\right]}{\text{crop water requirements}\left[\mathrm{m^3}\right] - \text{effective rainfall}\left[\mathrm{m^3}\right]} \quad (2)$$

This ratio shows to what extent the irrigation water requirements are being met. RIS values of less than 1 indicate deficit irrigation in the area, while values larger than 1 indicate overirrigation [7].

2.3.2. *Energy indicators*

After analysing the water use in the different irrigation systems, various energy indicators have been analysed. Knowing the energy consumption is required to be able to compare this to the solar energy production and consumption. It can be calculated which part of the total energy consumption is currently provided by solar energy, and it can be seen if this part could be optimized or not. This is the case when the solar energy production is higher than the energy consumption, but when not all energy consumption is coming from the produced solar energy. The energy indicators are divided into two sub-categories: general energy indicators and solar energy indicators. The general energy indicators are mainly based on Rodríguez Díaz et al. [7], while the solar energy indicators have been defined during this study.

2.3.2.1. *General energy indicators.*

1. The total energy consumption [kWh] is the total amount of energy that is consumed for irrigation. This consumption includes energy for the abstraction, transportation and distribution of water to the crops. In this process, hydraulic pumps consume energy to give pressure to the water [39]. The energy consumption for irrigation partly depends on the irrigation method: pressurized systems such as sprinkler and drip systems require more energy than surface irrigation systems [1].

2. The total energy consumption per hectare [kWh ha^{-1}] is calculated using Eq. (3).

$$\text{total energy consumption per hectare } [\text{kWh ha}^{-1}] = \frac{\text{total energy consumption } [\text{kWh}]}{\text{total area irrigation system } [\text{ha}]} \tag{3}$$

3. The energy consumption per cubic metre of water supplied to the field [kWh m^{-3}] is the total energy consumption divided by the total volume of water pumped for irrigation in the corresponding year (Eq. (4)).

$$\text{energy consumption per cubic metre of water } [\text{kWh m}^{-3}] = \frac{\text{total energy consumption } [\text{kWh}]}{\text{annual irrigation water supply } [\text{m}^3]} \tag{4}$$

4. The total installed power [kW] is the sum of the power of all hydraulic pumps that are being used in the irrigation system.

5. The installed power per hectare [kW ha^{-1}] is calculated using Eq. (5).

$$\text{installed power per hectare } [\text{kW ha}^{-1}] = \frac{\text{total installed power } [\text{kW}]}{\text{total area irrigation system } [\text{ha}]} \tag{5}$$

6. The installed power per cubic metre of water supplied to the field [kW m^{-3}] is the total installed power divided by the total volume of water pumped for irrigation in the corresponding year (Eq. (6)).

$$\text{installed power per cubic metre of water } [\text{kW m}^{-3}] = \frac{\text{total installed power } [\text{kW}]}{\text{annual irrigation water supply } [\text{m}^3]} \tag{6}$$

2.3.2.2. Solar energy indicators.

1. The solar energy production [kWh] is the amount of solar energy that is being generated by the solar plant.

2. The consumed solar energy [kWh] indicates the part of the produced solar energy that is consumed by the irrigation system itself.

3. The sold solar energy [kWh] is the part of the produced solar energy that is not consumed by the irrigation system itself but that is being sold to the national energy grid.

4. The ratio of solar energy to total energy consumption [−] indicates the part of the total energy consumption that is provided by own-produced solar energy (Eq. (7)).

$$\text{ratio solar energy to total energy consumption } [-] = \frac{\text{consumed solar energy } [\text{kWh}]}{\text{total energy consumption } [\text{kWh}]} \tag{7}$$

5. The power of the solar plant [kW], or in some cases the sum of the powers of several (smaller) solar plants, is the maximum amount of electricity the solar plant could produce under ideal conditions.

6. The ratio of the power of the solar plant to the total installed power [−] is the part of the energy consumption that in theory could be provided by solar energy (Eq. (8)).

$$\text{ratio power solar plant to total installed power } [-] = \frac{\text{power solar plant } [\text{kW}]}{\text{total installed power } [\text{kW}]} \tag{8}$$

2.3.3. Financial indicators

Lastly, the financial indicators for irrigation have been analysed. This gives insight in whether the use of own-produced solar energy has helped irrigation systems in dealing with the increasing energy costs for irrigation. The indicators are partly based on Malano and Burton [28], complemented with indicators that have been developed during this study. The following financial indicators have been defined:

1. The total MOM (management, operation and maintenance) costs [€]. These include a) costs to the water authority, b) costs that are being made by the irrigation system itself, such as costs for the infrastructures in the system and loans of the staff, and c) energy costs.
2. The MOM costs per cubic metre of water supplied to the field [€ m^{-3}] are calculated by dividing the total MOM costs by the total volume of water pumped for irrigation in the corresponding year (Eq. (9)).

$$MOM\ costs\ per\ cubic\ metre\ of\ water\ [€\ m^{-3}] = \frac{total\ MOM\ costs\ [€]}{annual\ irrigation\ water\ supply\ [m^3]} \tag{9}$$

3. The total energy costs [€] are the total costs for the energy required to irrigate the system (energy required for the abstraction, transportation and distribution of water to the crops). Although the energy costs are included in the total MOM costs, these costs are also analysed separately to examine whether the use of solar energy has reduced the energy costs in the irrigation systems.
4. The total energy costs are also converted to energy costs per cubic metre of water [€ m^{-3}] (Eq. (10)) to indicate the energy price to supply one cubic metre of water to the field.

$$energy\ costs\ per\ cubic\ metre\ of\ water\ [€\ m^{-3}] = \frac{total\ energy\ costs\ [€]}{annual\ irrigation\ water\ supply\ [m^3]} \tag{10}$$

5. The profits of selling excess solar energy [€] are the profits an irrigation system receives for selling excess solar energy to the national energy grid.
6. The energy costs minus the profits of selling solar energy [€] show to what extent selling excess solar energy helps irrigation systems to cover their energy costs.
7. The ratio of the energy costs to the total MOM costs [−] shows which part of the total MOM costs originates from the energy costs for irrigation (Eq. (11)).

$$ratio\ energy\ costs\ to\ total\ MOM\ costs\ [-] = \frac{total\ energy\ costs\ [€]}{total\ MOM\ costs\ [€]} \tag{11}$$

8. The saved energy costs [€] are an estimation of the energy costs that the irrigation systems have saved by using own-produced solar energy instead of conventional energy. These costs are calculated by dividing the total energy costs by the consumed conventional energy, multiplying this by the consumed solar energy (Eq. (12)).

$$estimated\ saved\ energy\ costs\ [€] = \frac{total\ energy\ costs\ [€]}{consumed\ conventional\ energy\ [kWh]} * consumed\ solar\ energy\ [kWh] \tag{12}$$

3. Study area

In this benchmark study, six irrigation systems in the south of Spain have been compared: Valle Inferior, Santa María Magdalena, Bembézar, Guadalcacín, Genil Cabra and Zújar. The locations of these irrigation systems are shown in Fig. 1.

The irrigation systems are either located in the Guadalquivir, Guadalete-Barbate or Guadiana River Basins, all located in the south of Spain. The river basins are characterized for their semi-arid climate, with average precipitations ranging between 450 and 640 mm and evaporation varying between 1100 and 1400 mm per year, reaching evapotranspiration rates of around 10 mm per day in the months of June and July [40,41]. Precipitation varies significantly over the area and throughout the season. In the lower located areas the annual average rainfall can be below 400 mm, while in the mountains rainfall can go up to more than 1500 mm per year. Throughout the year, most precipitation takes place during spring and autumn, whereas in the other months precipitation is almost nil [41–44]. Due to climate change, predictions are that extreme events like heat waves and droughts will increase significantly, especially in the Mediterranean, where the three river basins of this study are located. This will reduce the water availability in the area, thereby affecting agricultural production and food security [45,46].

The reduced water availability caused by the region's semi-arid climate, combined with increasing frequency of extreme weather events, is already posing significant challenges for agricultural activities. To manage this scarce resource, water allocations are carefully regulated by the local water authorities of the Guadalquivir, Guadalete-Barbate and Guadiana River Basins. The maximum volume available for agricultural activities in all irrigation systems is set at 6000 m^3 ha^{-1}. However, these allocations, determined seasonally based on rainfall and reservoir levels, often fall below the maximum allowable volume due to prolonged periods of drought. This drought is caused by the lack of rainfall, which causes the circulating flows to be significantly reduced, and therefore the ecological flows of a normal situation may not be met [47].

The majority of the irrigation systems functions similarly. In the Valle Inferior, Bembézar, Guadalcacín, Genil Cabra and Zújar systems, water from the rivers flows to the main irrigation channel of each irrigation system, from where it is stored in reservoirs until the water is used for irrigation. From these reservoirs, pressure pumps are used to transport water to hydrants, from which water is being applied to the fields. In the Santa María Magdalena system, water from the river is directly transported to the reservoir. From there, like in the other systems, pressure pumps are used to deliver the water to the fields. In all systems, irrigation is organized on-demand, and the irrigation methods are surface, sprinkler and drip irrigation, varying between the six systems, as can be seen in Table 1. Table 1 also provides an overview of the general characteristics of the irrigation systems, including the total area, irrigated area, main crop types, and the year each system began using solar energy.

The six irrigation systems all started using photovoltaic solar energy within the last five years, starting from 2019. The capacities of the solar plants vary between 400 and 6000 kWp. The type of solar panels differs between the irrigation systems. In the Valle Inferior, Bembézar and Genil Cabra systems, the panels are equipped with tracking systems for the highest efficiency. The other solar plants include fixed panels. The solar panels in the Zújar irrigation system are bifacial panels: instead of only capturing radiation on the front side of the panels (monofacial panels), these bifacial panels also capture radiation on the back side, in order to increase the solar energy production (Fig. 2).

In some cases, excess of solar energy production is being sold to the national energy grid. However, selling excess solar energy is not allowed in every irrigation system. In Spain, if a solar plant is (partly) financed by subsidies from the government, it is not allowed to receive profits from selling solar energy in the first five years after construction of the plant. Currently, only the excess solar energy generated by the Valle Inferior and Bembézar irrigation systems is being sold to supplement the energy grid. The Valle Inferior system sells solar energy since the use of the plant in 2019. The Bembézar irrigation system sells excess solar energy to the grid since April 2023, meaning that during the temporal scale of this study—2021 and 2022—the system was not selling energy yet. In the case of the Santa María Magdalena system, the system is allowed to sell excess solar energy as the cost of the solar plant—4.5 million euros—has been paid entirely by the farmers of the system. However, due to administrative problems of the energy company, the irrigation system is not receiving any profits for giving their excess solar energy to the grid, while the energy company can sell this received solar energy.

Fig. 1. Location of the selected irrigation systems.

Table 1
General information of the selected irrigation systems, provided by the technical staff of the irrigation systems.

Irrigation system	River basin	Total area		Irrigated area		Irrigation method	Dominant crop types		Using solar energy since
[–]	[–]	[ha]		[ha]		[%]	[–]		[–]
		2021	2022	2021	2022		2021	2022	
Valle Inferior	Guadalquivir	18,945	18,945	18,401	18,036	38 % surface 62 % drip	40.2 % citrus; 11.3 % cotton; 7.9 % potato; 6.3 % fruit trees; 5.9 % wheat; 3.3 % olives; 3.3 % sunflower; 2.8% maize; 2.2 % almonds	41.8 % citrus; 9.9 % cotton; 7.7 % potatoes; 6.8 % wheat; 5.8 % fruit trees; 5.1 % sunflower; 3.4 % olives; 2.5 % almonds; 2.4 % tomato	2019
Santa María Magdalena	Guadalquivir	6000	6000	5856	5949	10 % sprinkler 90 % drip	66.4 % olives; 27.2 % cotton; 2.4 % wheat; 2.4 % almonds	75.9 % olives; 17.6 % cotton; 2.3 % almonds	2021
Bembézar	Guadalquivir	12,788	12,788	12,354	11,912	5 % sprinkler 95 % drip	61.8 % citrus; 8.3 % olives; 6.7 % wheat; 5.5 % cotton; 3.4 % almonds; 3.2 % maize; 2.3 % sunflower	61.9 % citrus; 7.8 % sunflower; 7.4 % olives; 6.9 % wheat; 5.1 % cotton; 3.7 % almonds	2020
Guadalcacín	Guadalete-Barbate	12,630	12,630	11,842	11,772	60 % sprinkler 40 % drip	28.6 % cotton; 18.5 % maize; 14 % sunflower; 8.9 % horticulture; 8 % alfalfa; 6.4 % olives; 2.1 % tomato	25.2 % cotton; 16.8 % maize; 11.7 % horticulture; 10.7 % sunflower; 7.9 % alfalfa; 7 % olives; 4.1 % tomato	2020
Genil Cabra	Guadalquivir	24,571	24,301	24,529	24,245	15 % sprinkler 85 % drip	49.8 % olives; 10.4 % wheat; 6.7 % almonds; 6.2 % cotton; 3.3 % garlic; 2.9 % sunflower	51.3 % olives; 10.9 % wheat; 7.3 % almonds; 5.4 % sunflower; 5.1 % cotton; 2.2 % garlic	2022
Zújar	Guadiana	21,568	21,568	19,808	19,221	6 % surface 19 % sprinkler 75 % drip	20.5 % maize; 20.4 % tomato; 14.8 % olives; 9.7 % horticulture; 4.6 % fruit trees; 3.9 % wheat; 2.9 % fig trees	20.5 % tomato; 16.3 % olives; 11.8 % maize; 9.3 % horticulture; 6.4 % wheat; 6.2 % sunflower; 5.3 % fruit trees; 2.7 % fig trees	2019

4. Results

4.1. Water use indicators

Table 2 presents the results of the water use indicators for the six irrigation systems. Analysing the data shows that several similarities and differences can be found between the systems, and between the data of the two studied years, 2021 and 2022.

The results show that in all irrigation systems, except the Guadalcacín system, the assigned water allocations are lower in 2022 compared to 2021, resulting in a reduced annual irrigation water supply. As mentioned before, in times of water scarcity, the assigned water volume can be lower than the maximum of 6000 m^3 ha^{-1}. This has increasingly been the case in recent years, due to the hydrological situation in Spain In 2021, this resulted in a decrease in assigned water allocations ranging from 33 to 58 % compared to a ‘normal' year with an allocation of 6000 m^3 ha^{-1}. In 2022, the decrease was even greater, varying between 33 % and 75 %.

These percentages vary between the irrigation systems, primarily due to their geographical location within the river basins and the corresponding levels of drought severity. The assigned water allocations are for example lower in the irrigation systems located in the Guadalquivir River Basin (Valle Inferior, Santa María Magdalena, Bembézar and Genil Cabra) than the irrigation systems located in the Guadalete-Barbate and

Fig. 2. Solar plants in the six irrigation systems. From top to bottom, left to right: solar panels with tracking system in the Valle Inferior system, where the small solar panel in between the panels is used for the tracking; fixed solar panels in the Santa María Magdalena system; solar panels with tracking system in the Bembézar system; fixed solar panels in the Guadalcacín system; solar panels with tracking system in the Genil Cabra system; and bifacial panels in the Zújar system.

Table 2
Results of the water use indicators for the studied irrigation systems in the years 2021 and 2022.

	Assigned water allocation		Annual irrigation water supply		Irrigation water supply per hectare		Effective rainfall		Irrigation water requirements		Relative irrigation supply	
	[m^3 ha^{-1}]		[m^3]		[m^3 ha^{-1}]		[m^3]		[m^3]		[−]	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Valle Inferior	3000	1500	59,517,032	43,398,737	3142	2291	74,264,400	61,988,040	142,112,390	150,819,791	0.42	0.29
Santa María Magdalena	3000	1500	9,042,368	6,966,904	1507	1161	17,958,000	16,812,000	40,505,952	44,528,265	0.22	0.16
Bembézar	4000	2000	46,327,000	25,104,640	3623	1963	52,788,864	49,553,500	92,890,898	94,757,653	0.50	0.26
Guadalcacín	6000	6000	59,352,489	60,082,568	4699	4757	44,937,540	61,078,680	78,500,618	83,133,864	0.76	0.72
Genil Cabra	2500	1500	54,993,230	36,650,121	2238	1508	80,371,741	83,911,353	189,216,910	187,101,560	0.29	0.20
Zújar	4000	4000	82,946,934	68,709,320	3846	3186	68,284,288	74,970,368	128,791,616	130,087,728	0.64	0.53

Guadiana River Basins (Guadalcacín and Zújar). Also within the Guadalquivir River Basin different water volumes are assigned, depending on the location of the system and the system's water rights. The Bembézar irrigation system, for example, receives a higher water allocation than the other systems located in the Guadalquivir River Basin.

Regarding the actual irrigation water supply per hectare, Table 2 and Fig. 3 illustrate that in the Valle Inferior (2021 and 2022) and Genil Cabra (2022) systems this supply is slightly higher than the assigned water allocation. This suggests that more water is used for irrigation than allowed. However, while the Hydrographic Confederation assigns a maximum water allocation for each irrigation season, it can also make 'extra' flows available from runoffs for the irrigation systems if the situation allows it, for example in rainy periods. These extra flows are not included in the assigned water allocation, and therefore the actual irrigation water supply per hectare can be higher than the assigned water allocation. Besides, if the irrigation systems have stored water from the previous irrigation season, this can also lead to a slightly higher irrigation water supply than the assigned water allocation in the next season.

Table 2 and Fig. 3 furthermore illustrate that the supplies in the Santa María Magdalena and Genil Cabra systems are relatively lower than those in other systems. The low irrigation water supplies also explain the low RIS values in these two systems. While the theoretical irrigation water requirements have stayed relatively constant in all systems in the two years, the RIS values have decreased, meaning that the annual irrigation water supply has reduced. In the years 2021 and 2022, the RIS values in the Santa María Magdalena system were 0.22 and 0.16, respectively, and in the Genil Cabra system 0.29 and 0.20. These low water supplies and RIS values are mainly due to the fact that the majority of the cultivated crops in these systems is olives: 66 % in 2021 and 76 % in 2022 in the Santa María Magdalena system, and 50 % and 51 % in the Genil Cabra system (Table 1). In the other systems, these percentages vary between 3 to 16 %. In the south of Spain, olives are generally cultivated under deficit irrigation. Deficit irrigation allows

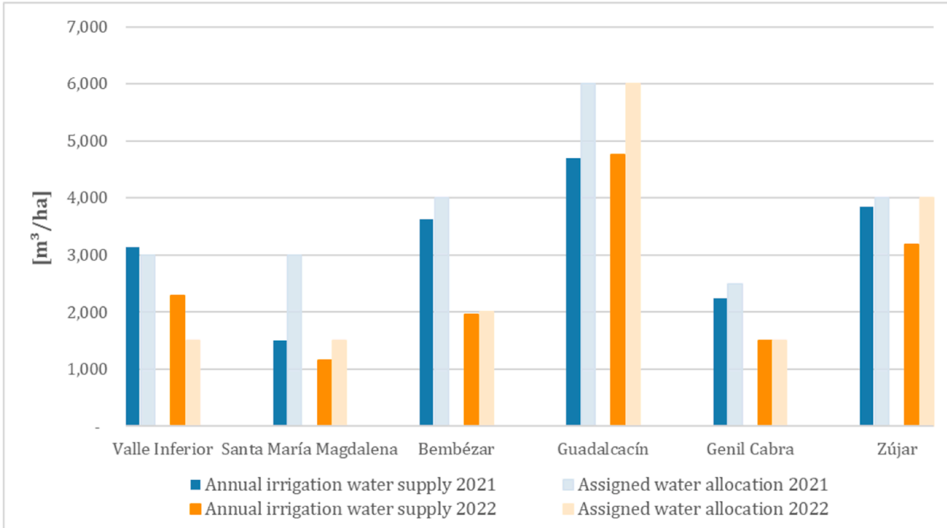

Fig. 3. Annual irrigation water supply [m^3 ha^{-1}] and assigned water allocation [m^3 ha^{-1}] for the studied irrigation systems in 2021 and 2022.

Table 3
Results of the general energy indicators for the studied irrigation systems in the years 2021 and 2022.

	Energy consumption		Energy consumption per hectare		Energy consumption per cubic metre of water		Installed power		Installed power per hectare		Installed power per cubic metre of water	
	[kWh]		[kWh ha^{-1}]		[kWh m^{-3}]		[kW]		[kW ha^{-1}]		[kW m^{-3}]	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Valle Inferior	9,071,914	6,174,807	479	326	0.15	0.14	12,360	12,360	0.65	0.65	2.08×10^{-4}	2.85×10^{-4}
Santa María Magdalena	6,791,101	4,877,502	1132	813	0.75	0.70	5800	5800	0.97	0.97	6.41×10^{-4}	8.33×10^{-4}
Bembézar	9,331,600	4,704,690	730	368	0.20	0.19	10,880	10,880	0.85	0.85	2.35×10^{-4}	4.33×10^{-4}
Guadalcacín	14,015,786	14,135,829	1110	1119	0.24	0.24	14,888	14,888	1.18	1.18	2.51×10^{-4}	2.48×10^{-4}
Genil Cabra	18,041,850	10,101,254	734	416	0.33	0.28	32,154	32,154	1.31	1.32	5.85×10^{-4}	8.77×10^{-4}
Zújar	20,015,710	16,659,664	928	772	0.24	0.24	21,400	21,400	0.99	0.99	2.58×10^{-4}	3.11×10^{-4}

farmers to decrease the irrigation water supply while limiting the reduction of the yield production, thereby maximizing the productivity per water input [48]. The limited water availability in the south of Spain has led farmers to use water more efficiently by making use of deficit irrigation, while at the same time maintaining their agricultural production. Fernández et al. [49] show that for an olive orchard in south-west Spain, the optimum irrigation supply is 1366 m^3 ha^{-1}, which corresponds to a RIS of 0.29, indicating deficit irrigation. Making use of deficit irrigation is thus a strategy for irrigation systems to deal with the low water allocations in the area, especially applied in areas with olive orchards.

4.2. Energy indicators

4.2.1. General energy indicators

The outcomes of the general energy indicators are presented in Table 3. As a result of the lower water allocations and irrigation water supplies in 2022 compared to 2021, the energy consumptions have also decreased in all irrigation systems, except in the Guadalcacín system, where the water allocation had not been reduced in 2022 (Fig. 4). Energy consumption reductions varied across the irrigation systems, with a 17 % reduction in the Zújar system, 28 % in Santa María Magdalena, 32 % in Valle Inferior, 44 % in Genil Cabra, and the largest reduction of 50 % observed in the Bembézar system.

While it is shown that the irrigation water supply is relatively low in the Santa María Magdalena system compared to the other systems, Table 3 shows that the energy consumption per hectare in this system is relatively high. Santa María Magdalena's low water supply combined with high energy consumption is due to the significant height differences in the area. Height differences of about 140 m are found in the area, resulting in higher energy requirements since more energy is needed for pumping the irrigation water uphill. This is also the case in the Guadalcacín irrigation system. Besides the height differences, the Guadalcacín system furthermore has a higher irrigation water supply (Table 2), which results in a higher energy consumption.

4.2.2. Solar energy indicators

Table 4 shows the results of the solar energy indicators. It should be noted that the Santa María Magdalena system started generating solar energy in July 2021 and the Genil Cabra system in May 2022. For this reason, the solar energy production in these systems is significantly lower in the first year of generating energy—relative to the power of the solar plant—compared to the production in the other systems.

Fig. 5 summarizes various results of the solar energy indicators: solar energy production, divided into consumed solar energy and sold solar energy. It can be seen that in the studied irrigation seasons only the Valle Inferior and Santa María Magdalena systems sell excess solar energy to the national energy grid. However, as will be shown in the next section and as touched on in Section 3, the latter one does not receive profits for transporting excess solar energy to the grid.

The remaining irrigation systems, Bembézar, Guadalcacín, Genil Cabra and Zújar, were not allowed to sell excess solar energy directly after the construction of the solar plant, as they received subsidies for (part of) the construction of the plant. As a consequence, these systems only monitor the solar energy production that is directly being used for irrigation in the system itself; they do not gather data on the solar energy production that is not used by the system. This can be shown by comparing the solar energy production in the Valle Inferior and the

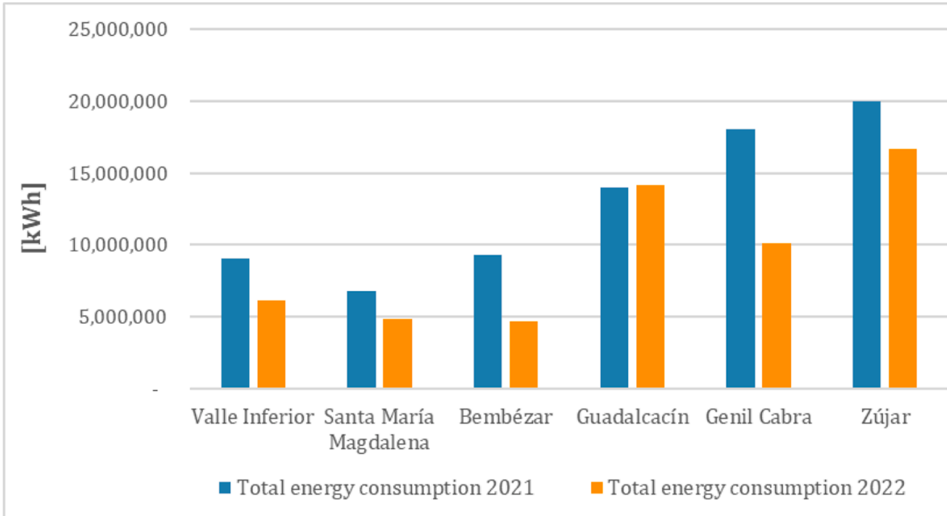

Fig. 4. Total energy consumption [kWh] for the studied irrigation systems in 2021 and 2022.

Bembézar systems, illustrated in Fig. 5. While the solar plants in these systems have a similar power, 6000 and 5250 kWp respectively, the solar energy production in the Valle Inferior system is significantly higher than in the Bembézar system: in 2022, the Valle Inferior system produced 10.9×10^6 kWh of solar energy, compared to 1.9×10^6 kWh in the Bembézar system. Based on the power of the two solar plants, the actual solar energy production could be similar in the two systems. However, since the excess solar energy produced in the Bembézar system is neither used within the system nor transported to the energy grid, this part of the production is not being monitored.

Table 4 and Fig. 5 furthermore show that the solar energy production in the Zújar system is lower than in the Guadalcacín system, while the capacity of the Zújar solar plant is larger. This can be ascribed to the fact that the Guadalcacín system has a higher water availability, and therefore more water and energy are used for irrigation. Again, these two systems only monitor the solar energy production that is being used for irrigation, resulting in a lower solar energy production in systems with lower assigned water volumes.

Regarding the ratio of solar energy to the total energy consumption, it is found that the Valle Inferior, Santa María Magdalena and Bembézar systems reach ratios of 0.40–0.57 (Fig. 6), meaning that around half of the total energy consumption is provided by own-produced solar energy. Data of the Valle Inferior and Santa María Magdalena systems, systems that also monitor the excess solar energy, show that the total solar energy production is higher than the total energy consumption in those systems. This implies that, in theory, no conventional energy would be required and thus a larger percentage of own solar energy could be used. However, van de Loo et al. [4] showed that in these large irrigation systems, where irrigation is on-demand, the energy needs are relatively constant during the day and night, meaning that a second energy source is required during the hours when no solar energy is being produced. For this reason, although the solar energy production is higher than the energy consumption, the possibility to completely rely on solar energy is excluded.

The Genil Cabra irrigation system is also expected to reach the above mentioned ratios. However, since the system started using solar energy in May 2022, in that year only 25 % of the total energy consumption was provided by solar energy. In the cases of the Guadalcacín and Zújar systems, the capacities of the solar plants are significantly lower compared to the other systems. Therefore, only a small percentage of the total energy consumed is provided by own-produced solar energy. Nevertheless, during the interviews conducted with the technical staff of the systems, it was mentioned that both systems are planning to increase the power of the solar plants in order to increase the use of solar energy.

4.3. Financial indicators

Table 5 presents the financial indicators for the six systems. It is found that the MOM costs remained relatively constant in all systems in the years 2021 and 2022. However, in the Guadalcacín system, these costs nearly doubled due to a significant rise in the energy costs. Table 5 indicates that, except for the Zújar system, total energy costs increased across all irrigation systems, despite a reduction in total energy consumption in almost all systems (as shown before in Fig. 4). These changes in the energy costs are further illustrated in Fig. 7.

The fact that energy costs in the Zújar system did not increase (with a 21 % reduction in 2022 compared to 2021) is attributed to more favourable conditions in the energy contract during the studied years. However, in the Valle Inferior, Bembézar and Genil Cabra systems, the energy costs doubled or nearly doubled (increases of 77 %, 128 % and 108 %, respectively), while the Guadalcacín system experienced an 302 % increase. The Santa María Magdalena system saw a smaller increase of 15 %. The significant rise in energy costs in 2022 can be mainly ascribed to Russia's invasion of Ukraine, which started in February 2022, and led to an exorbitant increase of the global energy prices. Besides, at the end of 2021 the energy prices were already high as an effect of the COVID-19 pandemic [50,51].

These rising energy costs underline the importance of optimizing solar energy usage to deal with the challenge they currently impose on large irrigation systems. Efficiently using self-produced solar energy not only reduces reliance on conventional energy sources, but also offers opportunities for economic benefits when excess solar energy is sold back to the national grid. Nonetheless, during the temporal scale of the study, only the Valle Inferior irrigation system received profits for transporting excess solar energy to the grid. Thanks to selling excess solar energy, the electricity bill has not been a problem in the Valle Inferior system, as it unfortunately has been in various other systems in the area [4]. As mentioned before, the Santa María Magdalena system does transport excess solar energy to the grid, but is not yet receiving profits for this, due to administrative problems of the energy company.

In the Valle Inferior system, the profits from selling solar energy are higher than the total energy costs, leading to a negative number when subtracting the profits from the costs. During the conducted interviews with the technical staff of the system, it was mentioned that the system currently uses these profits to pay off the costs of the construction of the solar plant, while maintaining a constant energy price for the farmers. In

Table 4
Results of the solar energy indicators for the studied irrigation systems in the years 2021 and 2022.

	Solar energy production		Consumed solar energy		Sold solar energy		Consumed conventional energy		Ratio solar energy to total energy consumption		Power solar plant		Ratio power solar plant to installed power	
	[kWh]		[kWh]		[kWh]		[kWh]		[–]		[kW]		[–]	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Valle Inferior	11,483,784	10,866,781	4,870,496	3,510,932	6,613,288	7,355,849	4,201,418	2,663,875	0.54	0.57	6000	6000	0.49	0.49
Santa M. Magdalena	1,409,217	6,728,488	834,781	2,510,949	574,436	4,217,539	5,956,320	2,366,553	0.12	0.51	3500	3500	0.60	0.60
Bembézar	3,697,834	1,880,580	3,697,834	1,880,580	0	0	5,633,766	2,824,110	0.40	0.40	5250	5250	0.48	0.52
Guadalcacín	691,679	653,139	691,679	653,139	0	0	13,324,107	13,482,690	0.05	0.05	400	400	0.03	0.03
Genil Cabra	0	2,507,122	0	2,507,122	0	0	18,041,850	7,594,132	0.00	0.25	4000	4000	0.12	0.12
Zújar	469,804	566,523	469,804	566,523	0	0	19,545,906	16,093,141	0.02	0.03	1220	1220	0.06	0.06

the future, after paying off the solar plant, setting the energy price at zero was mentioned as a possibility by the irrigation system.

Table 5 furthermore presents the estimated energy cost savings, which reflect the amount saved by irrigation systems using own-produced solar energy instead of purchasing conventional energy. These saved costs are approximations, as an average energy price during the year is assumed rather than accounting for varying energy tariffs throughout the day and across months. Nevertheless, it provides an estimate of how much an irrigation system could reduce its energy costs by implementing solar energy. This information could assist similar irrigation systems in estimating the payback period for their solar plant investment.

4.4. *Discussion key results*

The results of this benchmark study reveal several critical insights into the water and energy use, as well as the integration of solar energy, in large irrigation systems in southern Spain.

First, it is evident that most systems received reduced water allocations from the water authorities during the studied years. This reduction, driven by the challenging hydrological situation in Spain, directly led to lower energy consumption across the irrigation systems. Despite these reductions in energy use and the integration of solar energy, energy costs have increased in almost all systems—doubling or even tripling in some cases. This rise is primarily attributed to external factors, including the global energy crisis exacerbated by geopolitical events. To counteract these high energy costs, the Valle Inferior system sells its excess solar energy to the national energy grid, generating profits that help offset expenses. However, irrigation systems that received subsidies for their solar plant construction are temporarily prohibited from selling excess energy, limiting their ability to address rising costs effectively.

These restrictions also affect how solar energy production is monitored. Systems unable to sell or transport excess solar energy only account for the energy used directly for irrigation, leading to differences in reported solar energy production. For example, while the Valle Inferior and Bembézar systems have similar solar plant capacities, the monitored solar energy production in Bembézar is significantly lower due to these limitations.

Regarding agricultural water management practices, all systems operate large-scale pressurized irrigation networks—primarily drip and sprinkler irrigation (Table 1)—resulting in high energy demands. This is a direct consequence of Spain's irrigation modernization efforts, which replaced traditional gravity-fed systems with energy-intensive pressurized methods. While all systems grow olives as a dominant crop, deficit irrigation—widely practiced in southern Spain to conserve water while maintaining production—is commonly applied across these systems.

Nevertheless, the application of deficit irrigation, just as other agricultural water management practices like the irrigation method and crop type, do not seem to significantly influence solar energy utilization. For instance, the Santa María Magdalena system, despite its low irrigation water supply and RIS value, achieved a solar energy-to-total energy consumption ratio of 0.51 in 2022. This is comparable to the Valle Inferior system, which supplies nearly twice as much water per hectare but exhibits similar solar energy usage patterns.

This finding underscores a shared and recurring challenge among these systems: the use of on-demand irrigation, which includes an irrigation schedule of 24 h per day. By allowing farmers to access water and energy at any time, including during nighttime, these systems require a secondary energy source when solar energy is unavailable. Consequently, even in systems where solar energy production exceeds total energy consumption, conventional energy sources remain indispensable for nighttime irrigation.

5. Discussion

The performed benchmark study puts forth several points of

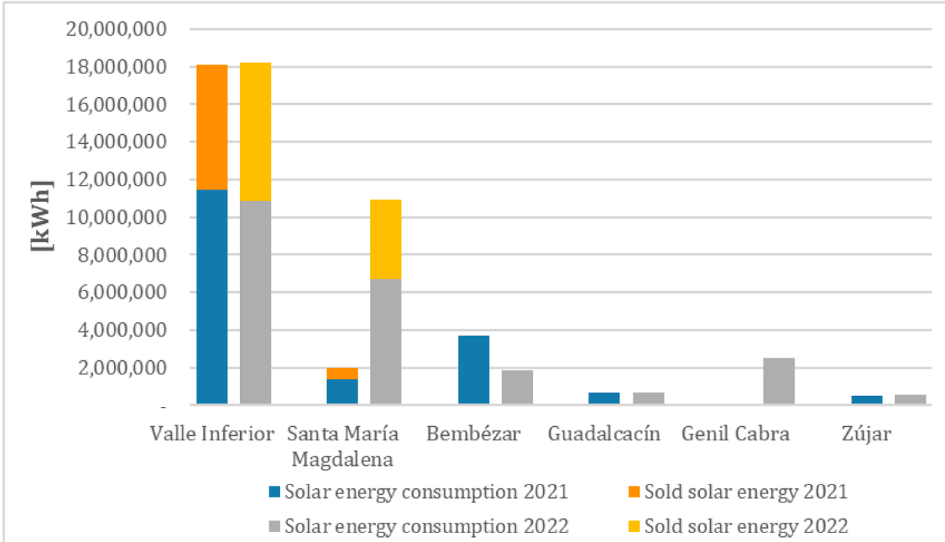

Fig. 5. Solar energy production, divided into consumed solar energy and sold solar energy, for the studied irrigation systems in 2021 and 2022.

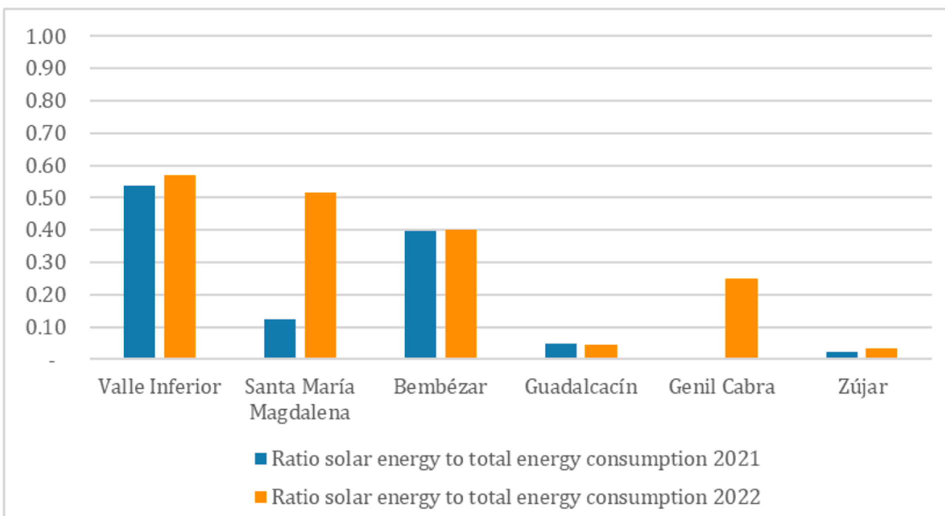

Fig. 6. Ratio solar energy to the total energy consumption for the studied irrigation systems in 2021 and 2022.

discussion regarding the use and optimization of solar energy in large irrigation systems. Rising energy demands and costs have driven the adoption of solar energy for irrigation, yet this study shows that its full potential remains unutilized. Despite some systems producing more solar energy than their total energy consumption, only about half of the energy used comes from solar production, mainly due to on-demand irrigation. Additionally, most systems are currently unable to sell excess solar energy, leaving a significant part of the produced solar energy unused. This raises questions about the future profitability of large solar plants and emphasizes the importance of exploring energy storage solutions or partnerships with the energy sector to prevent wastage. These issues, among others, are further explained below.

A consistent factor across all irrigation systems is their on-demand operation, which limits the utilization of own-produced solar energy. Water is continuously available to farmers, including at night. For the Valle Inferior system, van de Loo et al. [4] showed that the energy consumption is relatively constant throughout the day and night, meaning that another energy source is required during hours when no solar energy is being produced. Besides, due to the intermittency of solar energy production [23,25], own solar energy could never be relied upon as an energy source for systems that want to offer reliable on-demand irrigation during the day. Irrigation requires a constant and stable energy supply, which is in contrast with the intermittency of solar energy and of other renewable energy sources [5]. For this reason, to offer a reliable service, a second, constant energy source is needed.

The use of own-produced solar energy can be optimized if a change is made to irrigating during hours in which solar energy is being produced, as highlighted in previous study [4]. This includes adjusting the current 24 h irrigation schedule in all systems to, for example, 8 or 12 h schedules during the day [4]. However, this change can be difficult to implement, since farmers prefer irrigation at night to minimize water losses through evaporation, especially in years with strict water restrictions. Whether irrigating at night instead of during the day actually minimizes farmers' water losses can be questioned [52,53]. The idea of changing to irrigation during daylight hours, or at least increasing the number of farmers that irrigate during these hours, was mentioned by the technical staff of several systems during the conducted interviews. In the Zújar system, it was discussed that one way to encourage farmers to use water during the day is with time-of-use pricing: cheaper energy prices during the day and more expensive prices during the night. This

Table 5
Results of the financial indicators for the studied irrigation systems in the years 2021 and 2022.

	Total MOM costs		MOM costs per cubic metre of water		Total energy costs		Profits selling solar energy		Energy costs minus profits		Energy costs per cubic metre of water		Ratio energy costs to MOM costs		Saved energy costs	
	[€]		[€ m^{-3}]		[€]		[€]		[€]		[€ m^{-3}]		[–]		[€]	
	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022	2021	2022
Valle Inferior	4,337,668	4,449,267	0.07	0.10	583,904	1,034,793	771,843	1,345,385	−187,939	−310,592	0.012	0.012	0.13	0.23	676,891	1,363,836
Santa M. Magdalena	1,981,447	1,908,354	0.22	0.27	942,067	1,083,474	0	0	942,067	1,083,474	0.05	0.15	0.48	0.57	132,031	1,149,583
Bembézar	4,330,073	3,860,500	0.09	0.15	507,484	1,154,943	0	0	507,484	1,154,943	0.01	0.05	0.12	0.30	333,097	769,079
Guadalcacín	4,839,712	8,412,099	0.08	0.14	1,144,996	4,598,248	0	0	1,144,996	4,598,248	0.02	0.08	0.24	0.55	59,439	222,752
Genil Cabra	4,953,747	5,467,033	0.09	0.15	1,828,724	3,811,068	0	0	1,828,724	3,811,068	0.03	0.10	0.37	0.70	0	1,258,184
Zújar	5,498,052	5,165,795	0.07	0.08	2,061,406	1,638,780	0	0	2,061,406	1,638,780	0.02	0.02	0.37	0.32	49,548	57,690

would require telemetry systems that record hourly water consumption, but these are currently not very common in irrigation systems [4]. In the Genil Cabra system, time-of-use pricing was also considered as an option to stimulate irrigation during the day. However, this is expected to cause resistance among farmers, since farmers then also will want to distinguish different energy prices for different irrigation methods and for plots with different height differences, which both influence the energy needs.

Keeping a 24-h schedule can also have benefits when irrigation systems are able to sell excess solar energy, counteracting rising energy costs. Regarding the total energy costs, these have increased in almost all irrigation systems in 2022 compared to 2021. This occurred despite significant reductions in consumed conventional energy in most systems, attributed to lower water allocations and the increased use of own-produced solar energy. Although conventional energy consumption decreased, energy costs continued to rise. These increasing costs can be mainly ascribed to the wake of the COVID-19 pandemic, which triggered growing international energy demand, and Russia's invasion of Ukraine, which led to a significant energy crisis worldwide [50,51].

Selling excess solar energy, as demonstrated by the Valle Inferior irrigation systems, allows systems to mitigate these rising costs. In years with relatively low water allocations and therefore low energy consumptions, a large part of the produced solar energy could be sold to the national energy grid. This provides dual benefits: managing rising energy expenses and offsetting the impacts of reduced agricultural production due to the drought. However, in Spain, subsidy programs limit the ability of irrigation systems to profit from selling solar energy. When a solar plant is (partly) financed by government subsidies, profits from selling solar energy are not permitted for the first five years after the construction of the plant.

It is reasonable that when irrigation systems receive these subsidies, they are not allowed to receive *all* profits from selling excess solar energy. However, for multiple parties it could be beneficial to come to an agreement about letting irrigation systems sell excess solar energy, even if sold at a reduced price in the first five years. Besides bringing economic benefits to the irrigation systems, which can especially be crucial for these systems in dry years, it can furthermore help the energy network to increase their share of renewable energy. Currently, a large part of the produced solar energy in irrigation systems is not being used: the solar energy is not used for irrigation due to the lower water allocations and therefore the low energy requirements, and neither is it transported to the energy grid. Allowing irrigation systems to directly sell their excess solar energy after the construction of the plant, even at a reduced price, could increase the national use of renewable energy and thereby decrease its use of conventional energy. This is in line with the objectives of the European Green Deal, which aims to reduce the usage of fossil fuels. As mentioned before, the target of this deal is to derive 40 % of total energy from renewable energy sources, like wind and sun, by 2030, and to achieve climate neutrality by 2050 [13].

A well-known challenge of the transition from fossil fuels to renewable energy sources is handling the increasing amount of generated renewable energy, and particularly its intermittency. In Spain, the annual generation of photovoltaic solar energy increased from 9252 GWh in 2019 to 37,472 GWh in 2023 [54], indicating an increase of 405 % in 5 years. This rapid growth in renewable energy production highlights the grid's need for enhanced reliability and flexibility, a challenge faced by energy systems operators worldwide [55–58]. Furthermore, the integration of renewable energy is affecting the energy market: adding renewable energy production to the grid leads to lower load requirements during the day and higher load demands at night (also known as the duck curve), resulting in lower daytime energy prices and higher prices during the night [59–61]. In the last years, some European countries, such as Germany, France and the Netherlands, have even experienced negative energy prices during periods of high renewable energy production [62]. Since April 2023, Spain has also recorded negative energy prices during certain hours of solar energy generation

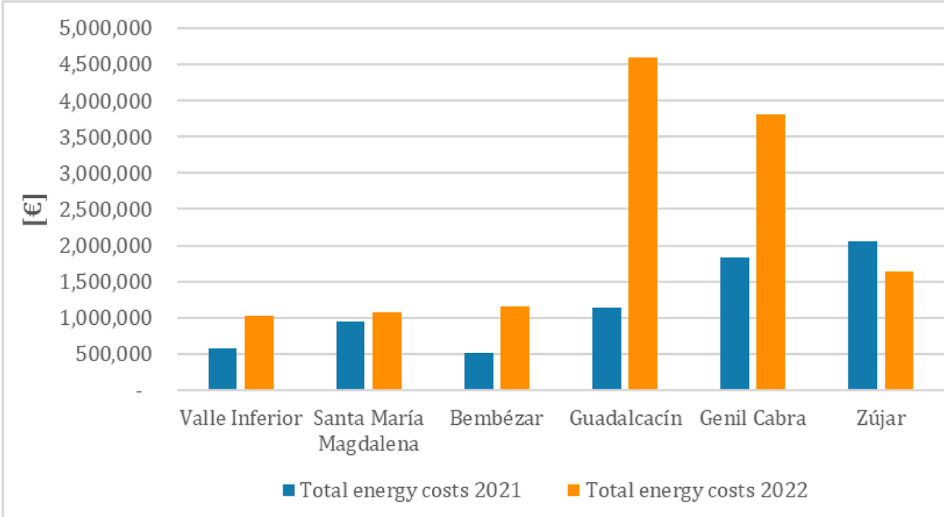

Fig. 7. Total energy costs [€] for the studied irrigation systems in 2021 and 2022.

[63].

Due to these changes on the energy market, it can be questioned whether in the future it will still be profitable for irrigation systems to sell excess solar energy to the grid. This has been questioned by the technical staff of the Valle Inferior irrigation system. They indicated that the profits for selling excess solar energy per kW have been declining since they began selling energy in 2019. This raises concerns about the long-term viability of selling excess energy. In 2024, in the months April, May and June, the irrigation system was forced to limit the production of its solar plant to avoid paying costs for transporting excess energy to the grid during periods of negative energy prices. This led to energy production levels below the plant's maximum potential and those of previous years. As a consequence, the discharge of excess solar energy to the grid during these months was significantly lower compared to prior years [64].

This dynamic energy market, together with the fact that a large part of the produced solar energy remains unused in various irrigation systems, asks for ways to store the solar energy in the systems itself. Storing solar energy allows irrigation systems to use their own-produced solar energy at another moment. As a consequence of the negative energy prices which have been mentioned above, the Valle Inferior irrigation system is currently studying the possibilities of installing solar batteries. The system indicates that the use of batteries will not only economically optimize the operation of the solar plant but will also reinforce their commitment to using clean energy. However, the technical staff of the Valle Inferior irrigation system indicated that they are still uncertain about the feasibility of battery storage. They expressed concerns about the payback period of batteries, which is not significantly shorter than their lifespan, making it a potentially risky investment. Nevertheless, increasing their self-consumption would ensure that future fluctuations in the energy market will have less impact on the system than they do now [65]. Securing energy sovereignty is of big importance for irrigation systems to continue irrigation operations without being constrained by high energy prices or other market dynamics. Moreover, reducing dependency on the national energy grid is one of the main drivers for irrigation systems to begin integrating solar energy.

Another technology to store solar energy, or other renewable energy, is pumped storage hydropower. Pumped storage hydropower is a clean, green, reliable, and affordable technology for energy storage, currently providing more than 90 % of all stored energy worldwide, outweighing lithium-ion and other battery types [58]. It operates by storing excess renewable energy as potential energy. During periods of high renewable energy generation but low energy demand and prices, water is pumped uphill to a higher reservoir. When demand and prices increase, the stored water is released to generate energy by flowing through a turbine [57].

For solar energy storage, water can be pumped uphill during daylight hours, utilizing the produced solar energy, and later released to generate energy as needed. In irrigation systems, pumped hydro energy storage could be implemented in two primary scenarios. First, energy could be generated during hours when solar energy is unavailable, ensuring sufficient energy supply for the irrigation system. This approach maximizes the use of own-produced solar energy, thereby reducing reliance on conventional energy and its associated costs. Moreover, as mentioned before, it also minimizes vulnerability to fluctuations in the energy market.

Secondly, pumped storage hydropower could be used to generate energy during periods of higher energy prices, allowing irrigation systems to sell the generated energy at a premium. This strategy not only maximizes economic returns but also alleviates pressure on the energy grid. Rather than transporting excess energy during hours of high solar energy production—when the grid is already saturated—energy can be transported during peak consumption hours, such as early morning or late afternoon. This dual benefit could significantly enhance both irrigation system operations and grid stability.

However, the feasibility of implementing pumped hydro energy storage in irrigation systems merits further investigation, for example on the amount of water that can be pumped and stored, the geographical suitability of the area, and the economic rationale of it, considering the investment costs and the economic benefits it could generate. Although pumped hydropower storage is an effective way to store excess renewable energy, the technology is limited by its geographical requirements [27]. For example, the Valle Inferior, Genil Cabra and Zújar systems lack significant height differences, making this solution impractical in their cases. However, systems like Santa María Magdalena, Bembézar and Guadalcacín could leverage the height differences in or near their regions to implement such solutions effectively.

An example is the Genil Margen Izquierda system, which already utilizes height differences to let water flow into the fields. Although not included in this benchmark study due to its lack of solar energy integration, this system lifts water to reservoirs located approximately 70 and 100 m higher using conventional energy at night, benefiting from lower nighttime tariffs due to an existing energy contract with reduced rates during nighttime hours. Together with the Guadalquivir Hydrographic Confederation, plans are underway to construct a solar plant with a capacity of 9 MWp. Following its construction, water would be pumped uphill during daylight hours using solar energy, optimizing energy use and reducing reliance on conventional sources. Additionally, the system's technical staff has expressed interest in exploring pumped hydropower storage as a future solution to store excess solar energy.

Increasing the consumption of own-produced solar energy in irrigation systems, either by adjusting irrigation schedules or by storing excess energy for later use, as outlined earlier in this text, not only reduces the system's energy costs and enhances their energy sovereignty, but also serves as a means of differentiation from other systems. In January 2023, the Valle Inferior became the first irrigation system in Spain to receive the ECO20 certification for its solar energy use [66]. This certification guarantees that the energy consumption of a company or organization originates from self-produced solar energy, thereby highlighting the use of clean and non-polluting sources. The Valle Inferior system received the certification in its Silver category, which certifies a renewable energy self-consumption between 50 and 70 %. In addition to using its own-produced solar energy, the system also purchases renewable energy from the market, ensuring that 100 % of its energy comes from renewable energy sources. With its average annual use of solar energy, the Valle Inferior system avoids the emission of approximately 952 tons of CO_2 per year. The ECO20 certificate highlights that the irrigation system uses renewable energy to transport the water to its fields. Given the growing appeal of sustainable brands, this certificate could become a competitive advantage for agricultural production in irrigation systems that obtain it.

While solutions can be found to maximize solar energy use in irrigation systems, the results of the benchmark study raise the question of whether it is profitable for irrigation systems to construct a large solar plant of several MWs, as has been done in the Valle Inferior, Santa María Magdalena, Bembézar and Genil Cabra systems. The production of solar energy depends on the size of the solar plant, the weather and the time of the year. The latter two factors cannot be modified and depend on meteorological conditions [23–25], but the size of the plant is a decision made by the irrigation system itself. Currently, about half of the total energy consumption comes from own -produced solar energy, while the other half comes from conventional energy, as energy needs are relatively constant during the day and night. If irrigation systems continue to offer on-demand irrigation with a 24-h irrigation schedule, the energy supply during the day could also be provided by own-produced solar energy from a plant with a smaller capacity. A larger solar plant brings higher investment costs, while in various systems, a significant part of the produced solar energy is currently unused and not sold to the grid. On the other hand, in years with a higher water allocation, a larger solar plant would increase the likelihood of meeting the system's energy needs with solar energy. Moreover, if the system is allowed to sell excess energy, a larger solar plant could result in higher economic benefits. However, this again depends on the energy prices for selling solar energy, which are dynamic and have been decreasing in recent years. This point of discussion was raised by the Zújar system: up to what capacity of the solar plant will it be profitable to increase its size, given that the prices for selling excess solar energy have dropped? To examine this, as also mentioned by van de Loo et al. [4], the next step would be to study profitability cut-offs, considering the investment costs of the solar plant, the use of own-produced solar energy by the system, the amount of solar energy that can be sold, and the dynamic energy prices.

Besides the size of the solar plant, other characteristics of the solar panels were also frequently discussed by the technical staff members of the irrigation systems, such as the type of solar panels. In a previous study, Narvarte et al. [5] stated that using tilting solar panels (with an N-S tracker) has several advantages over fixed panels. Tilting panels offer more constant energy production throughout the day, and the daily number of hours of energy production is extended (energy is generated earlier in the morning and later in the evening), which allows for pumping more hours with own-produced solar energy. Additionally, it is mentioned that the costs of an N-S tracker are lower than the costs of adding extra fixed panels to produce the same amount of energy. However, although tilting solar panels could be more beneficial for irrigation practices, many systems included in this study reported that they opted for fixed panels due to lower maintenance requirements. For example, the Santa María Magdalena system noted that experience had shown that tilting panels require a larger surface and more maintenance work, making them economically less beneficial. According to this system, the maintenance costs outweigh the costs of adding extra fixed solar panels to oversize the energy production or the costs of using conventional energy instead of own-produced solar energy.

Moreover, the use of floating solar panels instead of panels placed on land has been discussed with several irrigation systems. The Guadalcacín and Zújar systems mentioned that they are considering expanding their solar power by installing a floating solar plant. Many irrigation systems own reservoirs to store the water for irrigation, on which floating panels can be placed. One advantage of using floating solar plants is that they can reduce the water evaporation from the reservoir. Several studies have examined the evaporation losses of reservoirs. In Murcia, Spain, losses from evaporation of water from irrigation reservoirs can go up to 8 % of the available irrigation water supply [67], while in Almeria, also in Spain, estimations of evaporation losses of 17 % have been found [68]. To reduce evaporation of water and generate renewable energy at the same time, Redón Santafé et al. [3] analysed a floating solar plant with a capacity of 300 kWp on an irrigation reservoir in Alicante, located in south-east Spain. It was found that, besides generating 425,000 kWh per year, annual water savings of 25 % of the reservoir's storage capacity could be achieved by covering the reservoir with solar panels.

Floating solar panels not only reduce evaporation losses but also generate more energy than those on land. Because of the cooling effect of the water on the panels, the energy conversion efficiency is increased, resulting in solar energy productions of up to 10 % higher than on land [69]. Besides, the floating panels shield the water from solar radiation, reducing photosynthesis and weed growth in the reservoir, thereby improving its water quality. Moreover, no agricultural land is required for the solar plant, thereby maintaining the agricultural production capacity of the irrigation systems [3]. However, several limitations should also be considered while implementing floating solar panels in irrigation systems, such as the higher initial costs, the maintenance of the panels, and the variations in water level. Regarding the latter, although floating solar plants are prepared to lay flat on the reservoir's walls and bottom, solar energy production may be reduced due to the shadow created by the walls [70].

6. Recommendations

To optimize the integration of solar energy in large irrigation systems, several approaches can be implemented. First, adjusting irrigation schedules to align with daylight hours when solar energy is most available can significantly enhance the use of own-produced energy. Encouraging such shifts could involve time-of-use pricing strategies, where daytime irrigation is incentivized through lower costs, and supported by telemetry systems to track and manage water usage efficiently.

Energy storage solutions are essential to address the intermittency of solar energy and to ensure reliability. While battery storage offers flexibility, further research into its economic feasibility is needed, given concerns about the alignment of payback periods with battery lifespan. Pumped hydro storage, where geographically feasible, provides a compelling alternative, leveraging height differences to store and release energy in a sustainable manner.

The design and capacity of solar plants also play a crucial role. Optimizing plant size to balance energy needs with investment costs, particularly in the context of dynamic energy prices, can help systems achieve profitability. Incorporating innovative technologies, such as tilting panels for improved efficiency or floating solar panels to reduce water evaporation and improve energy conversion rates, could further enhance performance.

Policy adjustments are equally vital. Allowing irrigation systems to sell excess solar energy, even at reduced rates during the initial years after receiving subsidies, could provide critical financial relief while supporting national renewable energy goals. This flexibility would also encourage greater adoption of solar energy across irrigation networks.

Finally, obtaining certifications, such as the ECO20, can highlight a system's commitment to sustainability. These certifications not only underscore environmental stewardship but can also serve as a competitive advantage for agricultural products associated with sustainable practices. By showcasing their use of renewable energy, irrigation systems can differentiate themselves and potentially attract markets that value sustainability.

Collaborating with energy networks to address grid stability challenges and optimize energy storage and transportation strategies can further bolster the integration of solar energy. Strengthening these partnerships can help reduce pressure on the grid during peak solar production hours, improve the utilization of renewable energy, and create opportunities for shared innovation. By adopting these measures, irrigation systems can move toward greater sustainability, resilience, and economic viability.

7. Conclusion

This study examined the integration of solar energy in six large irrigation systems in southern Spain, shedding light on its potential and challenges. The findings underscore the growing importance of renewable energy in agriculture, particularly in regions where water and energy are critical for sustainable farming. While solar energy offers significant benefits, such as reducing energy costs and greenhouse gas emissions, its integration into large irrigation networks still presents challenges.

The integration of solar energy in large irrigation systems is primarily influenced by the on-demand operation of these systems. The 24-h irrigation schedules and farmers' preference for nighttime irrigation to minimize evaporation losses result in a reliance on conventional energy during non-solar hours, limiting the full utilization of solar energy. This underscores the critical need for systemic adjustments, such as innovative scheduling or energy storage solutions, to maximize the benefits of solar energy.

Other agricultural water management practices, including irrigation methods, deficit irrigation, and crop types, have a comparatively minimal impact on the effective use of solar energy as long as the systems operate on-demand. While practices like deficit irrigation, particularly in olive cultivation, are effective in addressing water scarcity, they do not substantially influence the integration of solar energy. This highlights the predominance of irrigation schedules and energy synchronization as determining factors for the successful utilization of solar energy in such systems.

The study also highlighted disparities in the ability of systems to sell excess solar energy, largely influenced by subsidy regulations. Energy costs have risen substantially in recent years, placing financial strain on irrigation systems and making efficient energy management critical. Allowing systems to sell surplus energy, even at reduced rates, could enhance financial viability and support broader renewable energy adoption.

Energy storage solutions, such as batteries and pumped hydropower, emerge as promising but underexplored strategies to support energy sovereignty. Energy sovereignty is of critical importance for irrigation systems, not only to ensure independence from fluctuations in the energy market but also to maintain reliable operations. Batteries provide flexibility, but their economic feasibility remains uncertain due to concerns like the alignment of payback periods with battery lifespans. Pumped hydropower, when geographically feasible, offers a sustainable alternative by utilizing natural height differences to store excess energy. Expanding research into these technologies could unlock new pathways for integrating renewable energy into irrigation. Additionally, technological improvements, such as the adoption of tilting or floating solar panels, present further avenues for optimization. These advancements not only enhance energy efficiency but also provide added benefits, such as reducing water evaporation and improving reservoir water quality.

The role of policy and certification in driving adoption cannot be overlooked. Certifications like the ECO20 not only validate sustainable practices but also offer competitive advantages in increasingly eco-conscious markets. Collaboration between irrigation systems and energy networks is essential to enhance grid stability, optimize energy usage, and foster innovation in renewable energy integration.

In conclusion, while solar energy integration in large irrigation systems has made significant strides, substantial opportunities for optimization remain. Addressing technical, economic, and policy challenges will be crucial for maximizing the benefits of solar energy, ensuring the sustainability of irrigation systems, and contributing to broader climate and energy goals. This research provides a framework for future studies and a roadmap for stakeholders aiming to enhance the synergy between solar energy and agricultural water management.

CRediT authorship contribution statement

Maaike van de Loo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emilio Camacho Poyato:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Juan Antonio Rodríguez Díaz:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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