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Defining the optimization strategy for solar energy use in large water distribution networks: A case study from the Valle Inferior irrigation system, Spain

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ABSTRACT

Irrigation modernization in Spain has brought significantly increased energy requirements. To provide the needed power, solar energy is rising in popularity. However, matching the availability of solar energy to irrigation demand remains a challenge. In the Valle Inferior irrigation system, while enough solar energy is produced on an annual basis, only 52 % of the energy consumed for irrigation is from own solar production, mainly due to the practice of night-time irrigation. For this system, this study explores two solar energy optimization scenarios. The first aims to optimize use of own solar energy by adjusting the current 24-h irrigation schedule to 8 or 12 h. The analysis finds that in situations where water availability is limited, this change can enable the annual percentage of own solar energy to be increased to 98 % of the total energy consumed. Nonetheless, such optimization of solar energy use gives rise to difficulties in the system itself, as farmers prefer to irrigate at night. In the second scenario, economic profits are optimized with the sale of excess solar energy. In this scenario, besides water availability and irrigation schedule, the optimum also depends on energy prices. Optimization is thus found to differ, depending on the optimization target, as well as water availability and the irrigation schedule used. This poses new operational challenges for large irrigation system management.

1. Introduction

With water sources becoming scarcer due to economic growth and the effects of climate change, new techniques are being implemented in the agricultural sector to use water more efficiently. One water-saving measure is the switch from surface irrigation to pressurized irrigation systems, like sprinkler and drip systems [1]. These systems are aimed at saving water, but have the undesired effect of significantly increasing the energy requirements of irrigation systems [2]. To tackle these higher energy requirements and the associated costs, solar energy, as an alternative source, is gaining popularity for irrigation systems. However, despite it being more sustainable than fossil fuels, the use of solar energy for irrigation presents challenges. An example is in matching the availability of solar energy to irrigation demand. This is especially problematic in large water distribution networks where irrigation is delivered on demand. This study, therefore, sought to better understand how produced solar energy and water use can be balanced in large irrigation systems.

A country where energy requirements for irrigation have particularly increased in recent decades is Spain. From 2002 to 2015, an intense irrigation modernization was undertaken in Spain to achieve required water savings in the agricultural sector [2]. This project, called the National Irrigation Plan (*Plan Nacional de Regadios*), was initiated in the mid-1990s in response to water scarcity in the country due to severe droughts. The National Irrigation Plan was a state-led project aimed to increase irrigation efficiency and reduce water stress during future

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drought periods [3]. The irrigation modernization project included lining old canals and replacing open channel distribution networks with on-demand pressurized networks. These investments were partly subsidized by the Spanish government to stimulate farmers to switch from surface irrigation to sprinkler and drip irrigation systems [2].

While it remains a question whether water savings have been achieved,[1] the switch to pressurized irrigation systems unquestionably caused an increase in the energy consumption of irrigation [2,4–6]. Irrigation systems in Spain were transformed from requiring relatively large amounts of water but low amounts of energy, to, in theory, requiring less water but much greater amounts of energy. Due to the rising energy prices in recent years [7], energy consumption has now become a significant factor in operational expenses for irrigation. Rodríguez Díaz et al. (2009) [8] even state that at times, modernizing irrigation systems, rather than being an advantage for farmers, creates a difficulty if energy requirements become excessively high. The problem has been compounded with the rising cost of energy from conventional sources. Thus, while farmers previously mainly had to deal with the threat of water scarcity, they currently also face the consequences of adapting their irrigation systems to water scarcity: higher energy requirements and thus higher energy costs. The two threats together – water scarcity and higher energy costs – now put pressure on farmers' economic sustainability [9]. Multiple studies emphasize the need to integrate both water and energy issues in future irrigation management decisions, thus focusing not only on optimizing water use but energy use as well [5,6]. However, integrating the optimization of solar energy use in irrigation system management has not been studied in detail.

Besides bringing rising energy expenditures, increased energy consumption for irrigation also means increased greenhouse gas emissions. As yet, agricultural systems depend largely on fossil fuels, which contribute to global warming in addition to being finite [10]. In Europe, to mitigate climate change, the European Green Deal seeks to reduce fossil fuel usage. Its target is to derive 40 % of all energy from renewable sources, such as the wind and sun, by 2030 and to achieve climate neutrality by 2050 [11]. Spain is one of Europe's countries with the highest number of hours of solar radiation, due to its geographical location. In the last decade, however, it has lagged behind in using its full potential for the production of solar energy [12,13]. This was mainly due to a 'solar tax' on owners of solar panels which discouraged the development of solar energy. Since abolishing the solar tax in 2019, the country has experienced growth in photovoltaic solar energy capacity.

In the agricultural sector, too, the use of solar energy to power irrigation systems is becoming more popular to reduce energy costs and minimize greenhouse gas emissions [9,10]. Initially, solar energy was applied mainly in small, farm-level irrigation systems, in places where no other energy sources were available [14]. Many studies have analysed or designed such standalone, solar-powered irrigation systems and demonstrated their feasibility in remote locations where electricity is unavailable or difficult to obtain [15–19]. However, in recent years, due to rising energy prices, solar systems have also started to be used in large water distribution networks at the irrigation district level. This transition has further been stimulated by the falling prices of solar technologies and the elimination of technological barriers that previously restricted the power of solar irrigation systems [20]. Large irrigation systems, moreover, typically have sufficient land at their disposal to construct large solar plants, for example, in unproductive areas [9]. These large schemes do not use standalone solar energy systems, but rather a combination of solar energy and conventional energy from the national 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 [20].

However, in these large water distribution networks, a challenge of using solar energy is to match the availability of solar energy, which fluctuates per day but also per season, to irrigation demand [21]. Conventional energy is generated as needed, so the supply of energy is readily matched to demand [22]. However, in the case of renewable energy, whether energy is being generated depends on the availability of the resource. This is an issue when renewable energy is used in irrigation systems: instead of having a constant energy supply, the energy supply is uncertain and dependent on meteorological conditions [4]. According to Balasubramanian & Balachandra (2021) [22] "transitioning electricity systems have moved from a situation of 'matching available supply with dynamic demand' to 'matching dynamic supply with dynamic demand'".

Using solar energy in large irrigation networks is technically complex, as the power requirements are substantial and most networks are organized on-demand; that is, water is continuously available to farmers, including at night. One example of such a system is the Valle Inferior irrigation system in the south of Spain, which started using solar energy in 2019 to meet the growing demand for energy while keeping energy costs manageable. It was one of the first large irrigation systems to adopt this technology in Spain. After it implemented solar energy, other irrigation systems in the south of Spain also started using solar energy, for example, the Santa María Magdalena system, the Bembézar system and the Genil Cabra system.

As the use of solar energy in large irrigation systems is a very recent phenomenon, and these solar installations are only a few years old, there are, to our knowledge, no previous studies that analyse the use of solar energy in these systems. Because matching produced solar energy to irrigation demand remains a challenge in large water distribution networks, the current research investigated how the use of water might be matched to the solar energy produced in large irrigation systems, using the Valle Inferior system as a case study. This research thus goes beyond the optimization of water and energy use in irrigation systems, to take on a new challenge: optimizing the use of *solar* energy in large irrigation systems, so as to deal with the higher energy requirements and associated costs while minimizing greenhouse gas emissions. By analysing the use of solar energy in the Valle Inferior system and optimizing its use there, the research contributes to a better understanding of balancing produced solar energy and water use in large irrigation water distribution networks applying solar energy, in Spain and elsewhere in the world.

The rest of the paper is organized as follows: Section 2 includes information on the study area, Section 3 explains the methodology that is used in this research, Section 4 presents the results, Section 5 contains the discussion, and, finally, Section 6 ends with the conclusions.

2. Study area

The Valle Inferior irrigation system is located in the Guadalquivir River Basin in Andalusia, Spain. The irrigation system has an area of 18,945 ha, extending from the town of Lora del Río to the city of Seville. The system counts about 2300 irrigators and 3000 plots. The median ambient temperature is around 18 °C, and average precipitation is about 500 mm per year.

The irrigation system is divided into nine sectors (Fig. 1). Each sector has its own reservoir, where water from a main channel is stored for irrigation. These reservoirs all have sufficient capacity to meet the maximum demand of the sector they supply for a period of three days during the summer season. Three of the reservoirs are entirely gravity fed; the other six reservoirs are mainly filled by gravity but also rely on a

[1] A commonly held belief is that switching from surface to drip irrigation results in water savings due to the improvement of irrigation efficiency, as runoff, percolation and conveyance losses are minimized [2]. However, whether the Spanish irrigation modernization project has resulted in water savings remains an open question. Studies have found that during the modernization, irrigated area expanded [3,39] and farmers switched to more water-intensive crops [3]. Besides this, several studies indicate that changing from surface to drip irrigation is more a water reallocation than a water saving [3,39–41].

Fig. 1. *Map of the Valle Inferior irrigation system and its division into nine sectors. The solar plant is located in Sector 6.* [Source: Comunidad de Regantes del Valle Inferior, n.d.].

pump to fill to capacity. From these nine reservoirs, pressure pumps are used to transport water to hydrants, from which water is applied to the fields. Irrigation is on-demand in the area, and the two main irrigation methods are surface and drip irrigation. Surface irrigation accounts for 38 % of the irrigated area and drip irrigation for 62 %. Surface and drip irrigation are distributed randomly in the area, so there are no sectors with only surface or only drip irrigation. In 2021, the year for which the irrigation water requirements were calculated, the main perennial crops cultivated in the Valle Inferior irrigation system were citrus (40 %), fruit trees (6 %), olives (3 %) and almonds (2 %). The main non-perennial crops were cotton (11 %), potatoes (8 %), winter wheat (6 %) and sunflowers (3 %).

The licensed water volume is assigned by the area water authority (Guadalquivir Hydrographic Confederation) [23]. Water 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. The maximum volume available for agricultural activities in the area is set at 6000 m^3 ha^{-1}. In times of water scarcity, the assigned water volume can be lower than this maximum. Indeed, this is increasingly the case in the river basin, due to the low precipitation of recent years. In 2021, the water allocation was set at 3000 m^3 ha^{-1}. In 2022, an extremely dry year, it was restricted further, to 1000 m^3 ha^{-1}, a decrease of 83 % compared to a 'normal' year with a concession of 6000 m^3 ha^{-1}.[2]

Since 2019, the Valle Inferior irrigation system has used photovoltaic energy from what was, at the time of this research, the largest solar plant of all Spanish irrigation systems. The plant has a capacity of 6 MWp and occupies 15 ha of land in Sector 6. The solar panels in the Valle Inferior system are equipped with tracking devices for the highest efficiency. Moreover, the photovoltaic solar plant is connected to the power grid. Thus, solar energy that is not consumed by the irrigation system is sold to the national energy grid. A telemetry system records the solar energy produced, consumed and sold to the grid every 15 min.

In the agricultural year 2020/2021,[3] the solar plant produced $11.1 \cdot 10^6$ kW h of energy. The total energy consumed by the irrigation system that year was $8.9 \cdot 10^6$ kW h. In theory, no conventional energy would thus be required to power the system's energy needs. However, instead of completely relying on own solar energy, only 52 % of the total energy consumed was provided by the produced solar energy. This is mainly due to the practice of night-time irrigation.

3. Methodology

In theory, the Valle Inferior irrigation system could be using more solar energy than is currently the case. This study, therefore, focused on analysing the performance of the solar plant in regard to two optimization targets: maximizing the share of own solar energy used in the irrigation system, thereby minimizing conventional energy use, and maximizing economic benefits from the "right" mix of grid and solar energy consumption and the sale of excess solar energy to the grid. The optimization strategies were not verified with optimization software to find the computational optimum. This is because, as this is the first study to investigate the use of solar energy in a large irrigation network, it was initially unknown what variables would influence the solar energy optimization in the system. Thus, without the use of optimization software, a first attempt at optimization is made based on available data. This was done by working out scenarios based on a study of the literature, analysis of data on water use and energy consumption in the system, and interviews with farmers and technical staff of the irrigation system.

3.1. Actual water use

First, the actual water use in the Valle Inferior irrigation system was obtained for each month of the agricultural year 2020/2021. The actual water use was then compared to the gross irrigation water requirements to determine the extent that the requirements of the system were being met. The requirements were calculated using Cropwat, based on the 2021 cropping pattern. To simplify the cropping pattern, only crops covering 2 % or more of the total area of the irrigation system were considered, as crops covering less than 2 % would not significantly influence the total irrigation water requirements. The requirements were calculated for the whole area (18,945 ha) minus the area of barren fields in system (544 ha): 18,401 ha. The calculated irrigation water requirements for the Valle Inferior system were converted to *gross* irrigation water requirements by dividing the irrigation water requirements by the scheme irrigation efficiency. A scheme efficiency of 82 % was used, based on an irrigation efficiency of 60 % for the area irrigated with surface irrigation and 95 % for the area irrigated with drip irrigation [24,25].

To calculate the requirements, various input data were required. Monthly evapotranspiration and monthly precipitation data were

[2] In May 2022, the Hydrographic Confederation reconsidered the restriction, and as of 11 May, the concession was revised to 1750 m^3 ha^{-1} for the remaining months of 2022. Compared to a normal year, this is still a decrease of 70 %. As the scenarios were already developed and calculated for the 1000 m^3 ha^{-1} assignment, this water assignment was used throughout the analyses.

[3] In this research, the temporal scale is annual, so as to show variations throughout the different seasons. The annual scale is given in terms of the agricultural year, from October to September. The first agricultural year in which the Valle Inferior system used solar energy was 2020/2021, so in this research the temporal scale is from October 2020 to September 2021.

obtained from the Andalusian Agroclimatic Information Network (*Red de Información Agroclimática de Andalucía*). In this research, data from the La Rinconada weather station were applied, as this station is located in the study area. Specific crop data, such as the *Kc* values and the length of the different growing stages, were obtained from the *FAO Irrigation and Drainage Paper No. 56* [26].

3.2. Actual energy consumption

After analysing the water use in the system, the energy consumption and solar energy production were analysed. As noted, Valle Inferior collects this data every 15 min using a Supervisory Control and Data Acquisition (SCADA) system. Though this analysis was done for every day of the agricultural year 2020/2021, only four consecutive days, 27–30 May 2021, are presented here in detail to illustrate the constraining parameters on the optimization.

The energy consumption and produced solar energy were first obtained throughout the year. Energy consumption (divided into conventional energy and solar energy) was then compared to the produced solar energy (divided into consumed and sold solar energy) to identify when during the year solar energy provided sufficient energy for the irrigation system and when it was not possible to completely rely on solar energy.

Because production of solar energy fluctuates not only per season but also during the day, after determining the system's energy consumption and solar energy production throughout the year, these parameters were also analysed throughout the day. Comparing the daily energy consumption with solar energy production again showed when solar energy could not be relied upon, but now on a daily basis, in the presentation here, for the four reference days, 27–30 May. These days were chosen to demonstrate the fluctuations of solar energy production, both from day to day and within a single day. This comparison of energy consumption and solar energy production in the area provides insight into the current relation between these parameters. To express that relation, two factors were calculated: the percentage of own-produced solar energy in total energy consumed (eq. (1)) and the percentage of solar energy consumed in the total produced solar energy (eq. (2)).

$$\textit{Percentage own solar energy in total energy consumed}\ [\%] = \frac{\textit{consumed solar energy}\ [kWh/year]}{\textit{total consumed energy}\ [kWh/year]} \quad (1)$$

$$\textit{Percentage solar energy consumed in total produced solar energy}\ [\%] = \frac{\textit{consumed solar energy}\ [kWh/year]}{\textit{produced solar energy}\ [kWh/year]} \quad (2)$$

To simplify the energy consumption throughout the day and month for the currently practiced 24-h irrigation schedule, the irrigation water, and thus energy consumption, was assumed to be equally distributed throughout the day and month, providing a constant energy consumption line for 24 h. Thus, the monthly energy consumption was divided by the number of days in each month. This assumption was necessary because the percentages of farmers irrigating during the day and at night were unknown, and these percentages may fluctuate as long as the system is not run at its maximum capacity (i.e., a water concession of 6000 m^3 ha^{-1}).

3.3. Interviews with farmers and technical staff

During the data analysis, interviews were conducted with farmers and technical staff of the Valle Inferior irrigation system. These had several purposes: to gain a clear overview of the study area, to discuss and obtain feedback on the scenarios to optimize the use of solar energy, and to include farmers' perspectives in the scenarios. A diverse group of farmers was interviewed, including different farm sizes, crops and irrigation methods.

The interviews with the farmers were divided into three parts. First, general questions were asked on farm characteristics, such as size of the farm property, type of crops and irrigation method. The second part consisted of questions about the irrigation schedule, to find out when farmers used water for irrigation and thus consumed energy. The interviews ended with questions about the water restrictions in the area. These restrictions may have influenced the choices farmers made regarding land uses.

The interviews with the technical staff of the irrigation system sought to acquire more detail about the Valle Inferior irrigation system. Furthermore, initial ideas for the scenarios were discussed with the staff to find out if the scenarios could be considered feasible in the area.

3.4. Scenarios to optimize the use of solar energy

After analysing water use and energy consumption, and obtaining the current relation between energy consumption and solar energy production in the Valle Inferior system, scenarios were worked out to adjust this relation to optimize the use of own solar energy. For the scenarios, it was decided not to make any infrastructural changes in the Valle Inferior irrigation system. Spain has already implemented substantial changes in water infrastructure, focused first on the construction of large reservoirs to store water and later on the aforementioned irrigation modernization project [27]. This study shifts the focus from water infrastructure to agricultural water management. This resulted in three scenarios: (1) business as usual, (2) adjusting the irrigation schedule and (3) selling the produced solar energy. These three scenarios were, furthermore, worked out for three assigned water volumes: 1000 m^3 ha^{-1} (corresponding to the water restriction in 2022), 3000 m^3 ha^{-1} (corresponding to the water restriction in 2021) and 6000 m^3 ha^{-1} (the maximum water concession in the area).

This research used the actual energy consumed in the agricultural year 2020/2021, when the water restriction was set at 3000 m^3 ha^{-1}. For that year, data on energy consumption was available on a monthly basis. For years with the maximum assignment of 6000 m^3 ha^{-1}, the annual energy consumption was known but not the consumption per month. For 2022, in which the water assignment was reduced to 1000 m^3 ha^{-1}, the actual energy consumption was not yet known for all the months. For these reasons, energy consumption in years with a water assignment of 6000 and 1000 m^3 ha^{-1} was estimated based on the actual energy consumption in the agricultural year 2020/2021. For the former, the energy consumption in agricultural year 2020/2021 was multiplied by two, and for the latter it was divided by three.

3.4.1. Scenario 1: business as usual

The business as usual scenario represents the current situation in the Valle Inferior irrigation system: irrigation is allowed 24 h per day, and part of the produced solar energy is used in the irrigation system itself with the remainder sold to the grid. For this scenario, it was calculated what percentage of the total energy consumed was provided by own-produced solar energy and what part was provided by the national grid, for each month of the agricultural year 2020/2021.

As previously noted, the amount of solar energy consumed throughout the day was known for every day of the agricultural year 2020/2021. To determine the percentage of own solar energy in the total energy consumed, the amount of solar energy consumed throughout the day was calculated as follows:

$$\textit{Consumed solar energy}\ [kWh/day] = \sum_{n=0}^{96} \min\{\textit{produced solar energy}_n[kWh/15\ min]; \textit{total consumed energy}_n[kWh/15\ min]\} \tag{3}$$

The share of own solar energy in total energy consumption was calculated per month by dividing the total consumed solar energy per month by the total energy consumption per month (as in eq. (1)).

The business-*as*-usual scenario was taken as the baseline for the other two scenarios. This way it could be determined whether or not the other scenarios led to an optimization of the use of solar energy.

3.4.2. Scenario 2: adjusting the irrigation schedule

The first optimization scenario incorporated adjustments to the irrigation schedule. Currently, irrigation is on-demand and allowed 24 h per day. Solar energy might be optimized if a change could be made to irrigating during daylight hours, when solar energy is being produced. This could maximize the use of own-produced solar energy, therefore minimizing the need to purchase conventional energy from the grid, also reducing the cost of energy. With this in mind, two sub-scenarios were worked out to synchronize irrigation demand with solar energy production.

- An irrigation schedule of 12 h instead of 24 h (scenario 2a)
- An irrigation schedule of 8 h instead of 24 h (scenario 2b)

For these sub-scenarios, it was again assumed that the consumed energy is distributed equally throughout each month. The amount of energy normally consumed in a 24-h day, however, was taken to be consumed in 12 or 8 h. In scenario 2a energy consumption per hour is twice that of the current baseline, for 12 h a day with irrigation starting at 08:00 a.m. In scenario 2b, the hourly energy consumption rate is three times the baseline for 8 h a day, with irrigation starting at 10:00 a.m.

The energy consumption for the two sub-scenarios was compared with the energy consumption in a 24-h irrigation schedule and the solar energy production for each day of the agricultural year 2020/2021. This enabled identification of situations in which own-produced solar energy provided enough energy for irrigation and those in which conventional energy was still required. Regarding the daily comparison of energy consumption and produced solar energy, only the days 27–30 May 2021 are shown in this paper.

3.4.3. Scenario 3: selling produced solar energy

Instead of maximizing use of own-produced solar energy for the irrigation system itself by adjusting the irrigation schedule, systems can also decide to use part of the produced solar energy and sell the remainder to the national grid. This is the current situation in the Valle Inferior system, so corresponding with scenario 1. In contrast, scenario 3 also includes 12- and 8-h irrigation schedules and, besides only calculating the percentage of solar energy consumed, this scenario also includes the cost of buying conventional energy and profit from selling solar energy.

In the Valle Inferior irrigation system, the sale of excess solar energy was fundamental in 2021 – a year in which energy prices rose sharply. First, thanks to the availability of the produced solar energy, the Valle Inferior irrigation community could buy less conventional energy. Second, the community gained substantial economic benefit from selling excess produced solar energy to the grid. These two factors together allowed the community "to counteract the exorbitant increase in prices, which has meant that the electricity bill has not been a problem in our community, as it has unfortunately been for many others in the Guadalquivir River Basin" [28]. With this in mind, scenario 3 explores the benefits derived from selling produced solar energy. Thus, this scenario does not aim to optimize the use of own-produced solar energy in the system itself, but instead to optimize the economic benefits from the produced solar energy.

First, the cost of buying conventional energy was calculated for every month of the agricultural year 2020/2021 as follows:

$$\textit{Energy cost}\ [€/month] = \textit{conventional energy required per month}\ [kWh/month] * \textit{cost of conventional energy}\ [€/kWh] \tag{4}$$

To determine the required amount of conventional energy, the consumed solar energy (eq. (3)) was subtracted from the required energy:

$$\textit{Conventional energy}\ [kWh] = \textit{required energy}\ [kWh] - \textit{consumed solar energy}\ [kWh] \tag{5}$$

Data on cost were provided by the Valle Inferior irrigation system. In calculating the cost of buying conventional energy, different energy periods have to be considered. In Spain, energy tariffs distinguish six time periods, considering the hour of the day and the month of the year. Period 1, P1, corresponds to the most expensive tariff and period 6, P6, to the cheapest tariff. The different energy periods throughout the year are presented in the supplementary materials.

After the cost of buying conventional energy was calculated, the profit from selling the produced solar energy that was not consumed by the Valle Inferior system was calculated. The prices for selling the solar energy were provided by the Valle Inferior irrigation system. These

Table 1
Actual water use and gross irrigation water requirements in the Valle Inferior irrigation system in the agricultural year 2020/2021.

Year [−]	Month [−]	Actual water use [m^3]	Gross irrigation water requirements [m^3]	Actual energy consumption [kWh]	Produced solar energy [kWh]
2020	October	3,431,307	9,774,827	475,375	662,137
2020	November	1,711,292	4,054,076	132,031	474,952
2020	December	0	0	98,581	416,830
2021	January	20,779	0	85,018	496,554
2021	February	34,694	1,261,268	85,134	543,231
2021	March	2,824,556	11,171,231	593,180	1,025,820
2021	April	6,622,591	10,810,869	869,107	995,461
2021	May	7,280,655	27,229,876	1,044,535	1,426,020
2021	June	10,245,744	32,432,607	1,597,119	1,445,793
2021	July	12,544,049	34,910,098	1,776,500	1,438,602
2021	August	9,618,202	29,324,482	1,443,680	1,261,572
2021	September	4,106,075	11,486,548	747,479	958,166
	Total	**58,439,944**	**172,455,884**	**8,947,739**	**11,145,138**

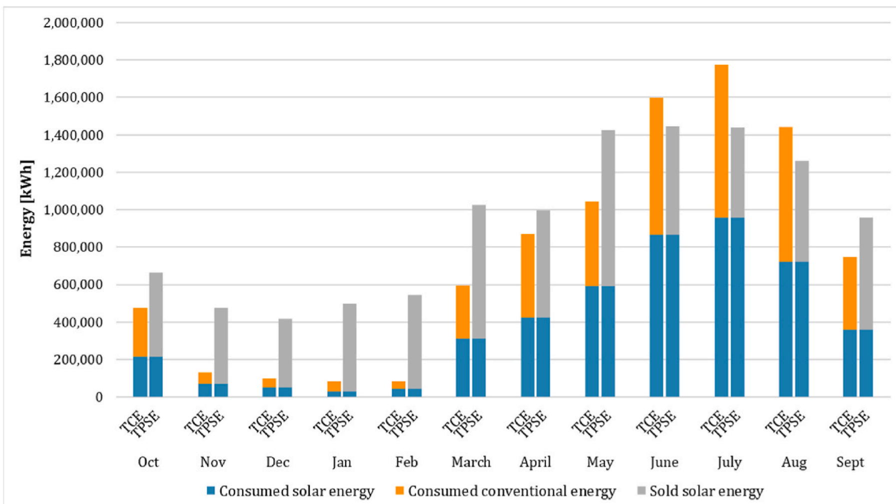

Fig. 2. Total consumed energy (TCE), divided into solar energy and conventional energy, and total produced solar energy (TPSE), divided into consumed solar energy and sold solar energy, in the Valle Inferior irrigation system in the agricultural year 2020/2021.

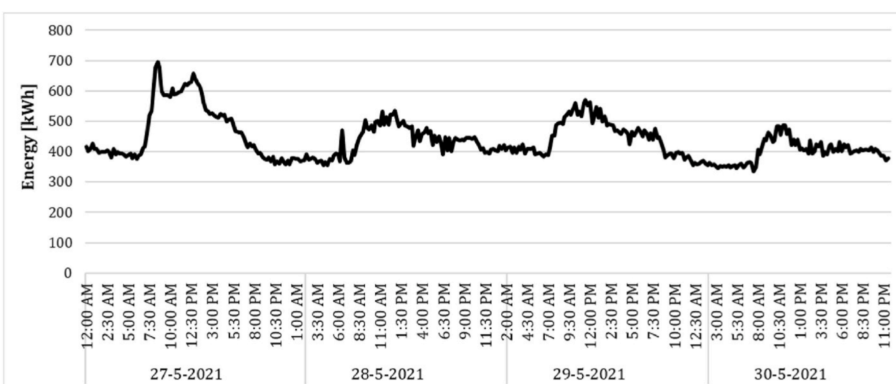

Fig. 3. Total energy consumed (solar energy plus conventional energy) in the Valle Inferior irrigation system throughout the day, 27–30 May 2021.

prices, like the prices for buying conventional energy, fluctuated throughout the year. Knowing both the cost of buying conventional energy and the profit from selling solar energy, these costs and profits were compared to determine whether the profit gained from selling solar energy covered the cost of buying conventional energy.

4. Results

4.1. Actual water use

Table 1 presents the actual water use in the Valle Inferior irrigation system and the gross irrigation requirements of the system. Comparison of the two shows that actual water use in the agricultural year 2020/2021 was significantly lower than the calculated irrigation requirements for that year: only 34 % of the requirements were met.

Table 2
Data on energy consumption and solar energy production in the Valle Inferior irrigation system for the agricultural year 2020/2021.

Total consumed energy [kWh]	8,947,739
Produced solar energy [kWh]	11,145,138
Consumed solar energy [kWh]	4,642,883
Share of solar energy in total energy consumption [%]	52
Share of solar energy consumed of total produced solar energy [%]	42

In the agricultural year 2020/2021, actual water use was restricted by water availability, as the assigned water volume was only 1000 m^3 ha^{-1}. However, even in a year with the maximum water allocation of 6000 m^3 ha^{-1}, the requirements would not be met. With an assignment of 6000 m^3 ha^{-1} and a total area of 18,945 ha, the total amount of water available for irrigation in the system would be 113,670,000 m^3 $year^{-1}$. In this case, 65 % of the requirements would be met. Water availability thus always restricts the actual amount of water used for irrigation in the area.

4.2. Actual energy consumption

The monthly energy consumption and solar energy production in the agricultural year 2020/2021 are also presented in Table 1. Fig. 2 shows the total energy consumption (TCE), divided into consumed solar energy and consumed conventional energy, and the total produced solar energy (TPSE), divided into consumed and sold solar energy. Fig. 3 traces the total energy consumption, but now zooming in on the days 27–30 May 2021. This figure shows that energy consumption is relatively constant throughout the day, as assumed in later steps of the analysis.

Fig. 2 indicates that only in the months June, July and August was the total energy consumed higher than the produced solar energy. This means that in the other months, potentially, only solar energy could be used in the Valle Inferior irrigation system. However, instead of relying solely on solar energy, just 52 % of the total energy consumed annually came from produced solar energy, and only 42 % of the solar energy produced annually was used in the system in the agricultural year 2020/2021 (Table 2).

This analysis of energy consumption and solar energy production suggests that, in theory, a larger percentage of own solar energy could be used, as in almost every month solar energy production was greater than energy consumption. However, besides fluctuating over the year, the amount of solar energy produced also fluctuates during the day (Fig. 4). These fluctuations occur, for example, due to clouds obscuring sunlight or due to heat, as in spring and summer, the region's high temperatures reduce the efficiency of the photovoltaic cells in the solar panels [29,30].

Fig. 4 presents energy consumption for the three water assignments (1000, 3000 and 6000 m^3 ha^{-1}) in the current situation with an irrigation schedule of 24 h per day. The figure shows that solar energy is

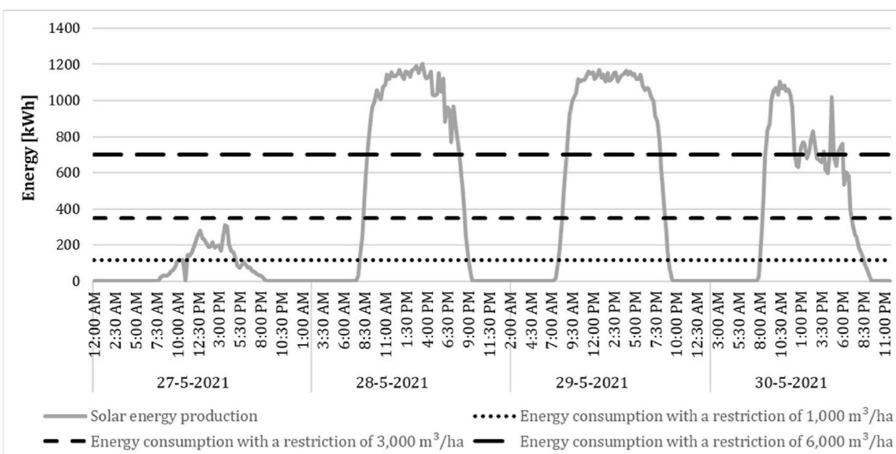

Fig. 4. Solar energy production and energy consumption throughout the day assuming a 24-h irrigation schedule and given the three water assignments, 27–30 May 2021.

Table 3
Percentages of own solar energy in the total energy consumed for each month of the agricultural year 2020/2021, given the three irrigation schedules (24, 12 and 8 h), for each of the three water assignments (1,000, 3000 and 6000 m^3 ha^{-1}).

	1000 m^3 ha^{-1}			3000 m^3 ha^{-1}			6000 m^3 ha^{-1}		
	24-h	12-h	8-h	24-h	12-h	8-h	24-h	12-h	8-h
	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]	[%]
October	42	81	96	39	73	86	36	62	61
November	39	77	98	38	73	94	37	68	89
December	37	74	99	36	70	94	35	64	86
January	39	76	99	37	72	95	36	67	89
February	42	83	99	41	79	97	40	75	92
March	46	87	97	42	79	92	39	70	74
April	48	90	95	43	76	81	38	57	46
May	54	97	98	50	90	90	46	67	49
June	55	96	98	50	85	64	44	44	32
July	55	99	100	51	79	57	40	39	29
August	52	98	99	48	84	65	42	43	32
September	47	90	97	44	81	87	40	64	52
Annually	**51**	**94**	**98**	**47**	**81**	**74**	**41**	**52**	**43**

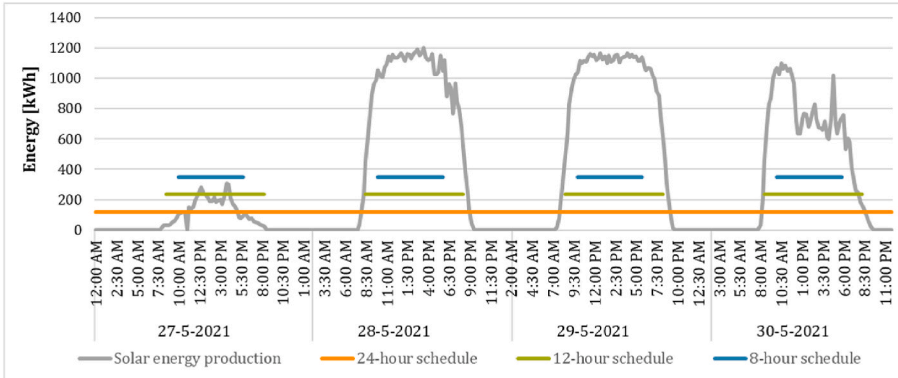

Fig. 5a. Produced solar energy and energy required for the three irrigation schedules (24, 12 and 8 h) with a water assignment of 1000 m^3 ha^{-1}, 27–30 May 2021.

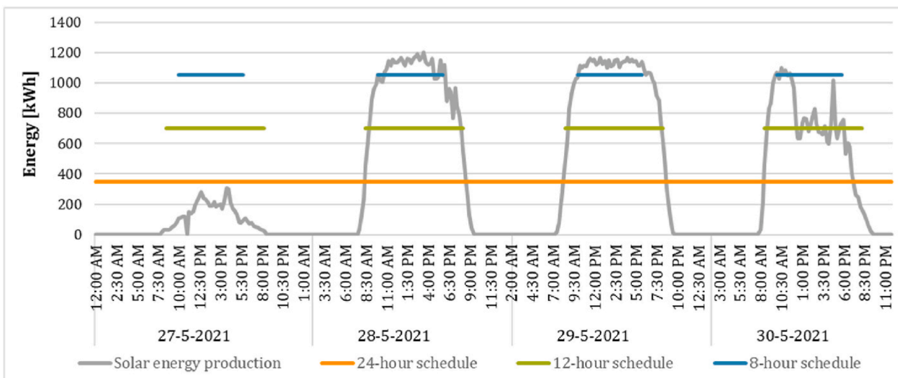

Fig. 5b. Produced solar energy and energy required for the three irrigation schedules (24, 12 and 8 h) with a water assignment of 3000 m^3 ha^{-1}, 27–30 May 2021.

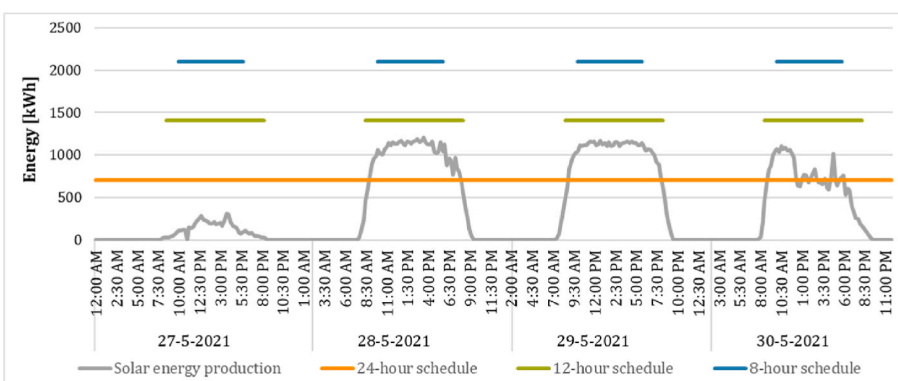

Fig. 5c. Produced solar energy and energy required for the three irrigation schedules (24, 12 and 8 h) with a water assignment of 6000 m^3 ha^{-1}, 27–30 May 2021.

only produced in daylight hours, from around 8:00 A.m. until 8:00 P.m., while water use, and therefore energy consumption, is allowed and takes place 24 h per day. It seems evident that the way the Valle Inferior irrigation system currently functions, with irrigation allowed 24 h per day, excludes the possibility for it to completely rely on solar energy, as another energy source is required during the hours when no solar energy is being produced. With this in mind, the scenarios worked out in the next section explore whether and how use of solar energy in the system might be optimized.

4.3. Scenarios to optimize the use of solar energy

4.3.1. Scenario 1: business as usual

The results of scenario 1 are presented in Table 3. The results of this baseline are discussed together with the results of scenario 2.

4.3.2. Scenario 2: adjusting the irrigation schedule

Fig. 5a, b and c show energy consumption for scenarios 2a and 2b for the three water assignments, respectively, together with energy consumption for the three irrigation schedules (24, 12 and 8 h) and solar energy production. In the figures, if the continuous lines depicting energy consumption are located under and in-between the line depicting produced solar energy, the irrigation system can, in principle, rely solely on solar energy. If the lines fall above or outside the produced solar energy line, conventional energy is required.

Table 3 presents the calculated percentages of solar energy in the total energy consumed for each month of the agricultural year 2020/2021. The table also shows the results for the first scenario, the baseline, which assumes a 24-h irrigation schedule.

The results of this scenario and the first scenario suggest that increasing the percentage of own solar energy in the total energy

Table 4
Profits from the sale of produced solar energy not used by the Valle Inferior irrigation system itself in the agricultural year 2020/2021, calculated for three water assignments and irrigation schedules.

	8-h	12-h	24-h
	[€]	[€]	[€]
1000 m^3 ha^{-1}	+567,390	+564,086	+535,446
3000 m^3 ha^{-1}	+9651	+37,554	−14,821
6000 m^3 ha^{-1}	−984,705	−931,674	−875,050

consumption depends on two factors: water availability and irrigation schedule. Under a water assignment of 1000 and 3000 m^3 ha^{-1}, it is easier to rely solely on own solar energy than under the higher water assignment of 6000 m^3 ha^{-1}. This is because in the scenarios with lower water assignments, less water is available and therefore less energy is required.

However, the results also show that despite situations where the percentage of own solar energy in the total energy consumption almost reaches 100 %, own solar energy cannot be relied upon as an energy source for irrigation systems. To offer a dependable service, a second, constant energy source is required.

Regarding irrigation schedule, with a 24-h schedule, conventional energy is always required to fill in during hours when no solar energy is being produced. On the 12- and 8-h schedules, complete or almost complete dependence on solar energy can be achieved on a yearly basis, though as noted above, another constant energy source remains required to ensure continuous availability of irrigation water. The 12- and 8-h irrigation schedules lead to almost a doubling of the percentage of own solar energy used under the lower water assignments, compared to a 24-h irrigation schedule.

Restricting the hours of irrigation means that the same amount of water must be distributed in a shorter time. Therefore, flow rates were also considered in analysing this scenario. The maximum flow rate of the Valle Inferior irrigation system, which is 1.2 l s^{-1} ha^{-1}, was exceeded only in the months June and July in the case of a water assignment of 6000 m^3 ha^{-1} and an irrigation schedule of 8 h, being 1.25 l s^{-1} ha^{-1} in June and 1.48 l s^{-1} ha^{-1} in July.

The results in Table 3 suggest there is room for optimization of the use of solar energy in the Valle Inferior irrigation system if a change is made from a 24-h irrigation schedule to a 12- or 8-h schedule. However, during the conducted interviews, several farmers expressed their preference for irrigating at night, to minimize water losses through evaporation, especially in years with low water allocations. One farmer explained that in a year with the maximum water allocation, of 6000 m^3 ha^{-1}, they would be willing to switch to irrigating during the day to optimize the use of solar energy, but in years with low water allocations they would be less willing to make this change. Whether irrigating at night instead of during the day actually minimizes farmers' water losses can be questioned.[4] Nonetheless, while it may be technically possible to switch to a 12- or 8-h irrigation schedule, implementing this scenario would require farmers to change their irrigation management. Indeed, Fig. 3 demonstrates that energy consumption remained relatively steady throughout the day. Farmers, therefore, do not appear to have made changes to irrigating during the day to optimize the use of solar energy in the system itself.

4.3.3. Scenario 3: selling the produced solar energy

The results of scenario 3 are presented in Table 4. The table reports the total profits for the agricultural year 2020/2021 (for the monthly calculations see the supplementary materials).

In the case of the two lower water assignments, 1000 and 3000 m^3 ha^{-1}, the results indicate that it is more profitable to change to a 12- or 8-h irrigation schedule. When using these irrigation schedules, the cost of buying conventional energy is reduced, while profits can still be made from selling excess solar energy.

In the case of a water assignment of 6000 m^3 ha^{-1}, the 12- and 8-h irrigation schedules are economically less beneficial than a schedule of 24 h. In the 12- and 8-h schedules, the produced solar energy is insufficient to be completely relied upon to deliver this amount of water. This means that instead of buying conventional energy at night, during hours with relatively low energy prices, energy now has to be bought during the day, when energy prices are higher. This increases the total energy costs. Additionally, less solar energy can be sold to the grid, as the majority of the produced solar energy is used in the system itself. For these reasons, under an assignment of 6000 m^3 ha^{-1}, it is more profitable to use a 24-h irrigation schedule.[5] This also allows farmers to continue irrigating at night. Thus, besides water availability and irrigation schedule, as in scenario 2, the optimization of scenario 3 also depends on energy prices. These prices, in turn, depend on the times energy is consumed and sold, and the interaction between these two factors.

While scenario 3 is easier to implement, as it does not require farmers to change their irrigation practices, potential problems for the energy network cannot be overlooked. Indeed, the intermittency of solar energy, and of other renewable energy sources, poses new challenges for power systems. Fluctuations in renewable energy, for example, affect the reliability and stability of energy networks [31–33]. This points to the need for further study of the integration of renewable energy into power systems. Additionally, in Spain there is an administrative obstacle. If a solar plant is partly financed by subsidies from the Spanish government, in the first five years after construction of the plant it is not allowed to receive profits from selling solar energy. Hence, for irrigation systems bound by this prohibition, the scenario of optimizing economic benefits from selling solar energy is not possible.

5. Discussion

The scenarios explored in this study point to several variables to be considered when seeking to optimize the use of solar energy in large irrigation networks. These are the amount of solar energy produced, the assigned water volume, the chosen irrigation schedule, the operational capacity of the irrigation system, and energy prices for both buying conventional energy and selling excess solar energy. The presented scenarios deal with these variables differently, thereby yielding different optimization solutions. Irrigation systems face the choice of whether to optimize the use of solar energy in the system itself or to optimize the economic benefits from selling excess solar energy. These variables and optimization targets are further discussed below.

First, optimization is influenced by the amount of solar energy being produced. This production depends on the size of the solar plant, the weather and the time of the year. The latter two factors cannot be modified, thereby ensuring that solar energy production is never constant. Indeed, because solar energy production is dependent on meteorological conditions, it will never be a reliable energy source for on-

[4] In the case of drip irrigation, which is the main irrigation method in the Valle Inferior system, the soil is wetted frequently, resulting in longer exposure to the atmosphere. When irrigating at night, the soil is still moist the next morning, while during the morning hours the evaporation rate reaches its maximum, and surfaces therefore dry rapidly during these hours [42]. Irrigation water on the soil thus evaporates immediately in the morning, meaning that evaporation losses may be less minimized by irrigating at night than assumed.

[5] In this research, the economic benefits from selling excess solar energy are calculated for the agricultural year 2020/2021 and with the corresponding energy tariffs in this year. However, energy prices are dynamic and due to the rise of solar energy, energy prices are currently changing (higher at night and lower during the day). These energy price dynamics will influence the outcomes of scenario 3.

demand irrigation, even if farmers only irrigate during daylight hours. Nevertheless, the size of the solar plant is a decision made by the irrigation system itself, and this decision can influence optimization outcomes. In the case of scenario 2, in which irrigation is performed only during the day, a larger solar plant would mean more solar energy production and therefore a higher chance of providing for the system's total energy needs with solar energy. In the case of scenario 3, in which solar energy is sold to the grid, greater solar energy production would mean that more energy could be sold or that less conventional energy would have to be bought during the day, depending on water availability and the chosen irrigation schedule. Of course, a larger solar plant would also bring higher investment costs. Therefore, a next step would be to determine profitability cut-offs, considering the investment costs of the solar plant, the use of solar energy by the system itself, and the amounts of solar energy that can be used and sold.

The assigned water volumes, irrigation schedule, and prices for buying conventional energy and selling excess solar energy were also found to influence optimization outcomes. In scenario 2, in which the irrigation schedule was adjusted from 24 h to 12 or 8 h, the use of own-produced solar energy in the irrigation system itself was optimized. This was the case for all three water assignments. Under scenario 3, however, the 12- and 8-h schedules were not always the most beneficial to optimize economic benefits. Up to a water assignment of 3000 m^3 ha^{-1}, the 12-h irrigation schedule was, from an economic viewpoint, the most beneficial. In the case of a water assignment of 6000 m^3 ha^{-1}, however, it was more beneficial to revert to a 24-h schedule. This was due to the influence of energy tariff schedules, as energy was less expensive at night.

Optimization outcomes thus differed depending on whether the optimization target was use of own-produced solar energy in the system or economic benefits from the produced solar energy. Furthermore, even within the scenarios, optimization outcomes differed for the different water assignments and irrigation schedules. To gain greater insight into when which irrigation schedule is more beneficial, further study of cut-off points between the variables is recommended. For example, in scenario 3, calculations could be performed to determine the water assignment up to which a schedule of 12 h is economically the most beneficial. Knowing this cut-off point can inform decisions on what irrigation schedule to use in a system, depending on the water assignment. As these water assignments are communicated by water authorities at the start of the irrigation season, this would seem a feasible strategy to pursue.

In addition, the irrigation system could decide to adjust irrigation times beyond those examined in this study, for both scenario 2 and 3 or for a combination of these scenarios. For example, if the 12-h irrigation schedule ran from 6:00 A.m. until 6:00 P.m., the system could first maximize its solar energy use, and afterwards, during peak hours of energy consumption, sell the produced solar energy to support the energy network. Nevertheless, in Spain, selling solar energy and thus optimizing the economic benefits from the investment in a solar plant also depends on whether subsidies were received for solar plant construction. In the case of the Valle Inferior system, excess solar energy could be sold and the economic benefits could thus be optimized. However, in irrigation systems that receive subsidies, no solar energy can be sold during the first five years of operation, which would exclude scenario 3 as possible, at least initially.

In cases where scenario 3 is possible, irrigation systems nonetheless should take into account that energy prices and price structures are dynamic. During the current research, energy prices in Spain, and throughout Europe, were changing due to the rise of solar energy. While at first energy prices were lower at night and higher during the day, daytime energy prices were falling due to the excess of solar energy production [34]. Such energy price dynamics will influence the outcomes of scenario 3.

Beyond the variables discussed above, the optimization of solar energy is restricted by several social and technical aspects. One of these is the attitudes of farmers, who were used to on-demand irrigation and expressed a preference for irrigating at night. According to irrigation system managers, the best way to encourage farmers to use water during the day is with time-of-use pricing, in which water is cheaper during the day and more expensive at night. However, this would require telemetry systems that record hourly water consumption, and these are not particularly common in irrigation networks. In addition, time-of-use pricing is unpopular among farmers. If irrigation systems did decide to change to irrigation during the day, the capacity of the infrastructure would have to be considered. Reducing the hours in which irrigation can be performed necessitates over-capacity in irrigation infrastructure. Providing this over-capacity in existing systems can be complicated, but for new systems it can be considered during system design. In such cases, the appropriate cut-off between over-capacity costs and economic energy efficiency should be studied.

The results for the Valle Inferior system indicate that the outcomes for the two scenarios – optimizing own solar energy use or optimizing economic benefits – differ under differing assumptions for the key variables. This finding points to new challenges in the management of irrigation systems. The operational strategy chosen by an irrigation system, either to optimize the use of own solar energy or to optimize economic benefits from selling solar energy, will depend on several variables which, moreover, can differ from year to year. Implementation of solar energy in large irrigation networks therefore adds another operational concern. In addition to 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 irrigation system is an interesting study case, as it is one of the first large systems to use solar energy. As no previous studies exist on how solar energy might be optimized in such large irrigation systems, this study represents a first step in this optimization process. No optimization software was used in the current research, as this is the first study to address the problem. However, future research can build on the presented results, for example, by using optimization software run with the variables found to influence the outcomes. To recap, main variables are solar energy production (dependent on the size of the solar plant and meteorological conditions), the assigned water volume, the chosen irrigation schedule, the operational capacity of the irrigation system, and energy prices for buying conventional energy and selling excess solar energy (dependent on the applicable energy tariffs). Using these variables in optimization software, the best solution for both optimization targets can be found: either optimizing the use of solar energy in the system itself, and thereby minimizing the use of conventional energy, or optimizing the economic benefits from selling excess solar energy. Such software could also be used to find an optimum solution combining both targets. In that case, it would indicate to what extent use of own solar energy in the system can be optimized while still making profits by selling excess solar energy. The freedoms of optimization are bounded by the operational capacity of the irrigation system, irrigation scheduling options and constraints, and the assigned water volumes.

Regarding the irrigation scheduling, many studies already performed optimization strategies on the irrigation schedule of irrigation systems, while at the same time maximizing crop yield [35–38]. García-Vila et al. (2012), for example, optimized the irrigation schedule at farm-scale for an irrigation system in southern Spain, using different water allocations (1000, 2500, 4000 and 5000 m^3 ha^{-1}) to also optimize it for situations with low water availabilities. In their optimization strategy, besides considering the water allocation, also the date on which the allocation is communicated to the farmers is taken into account, as knowing the assigned water allocation influences farm planning and management. Delaying the communication about the water allocation to the farmers (water authorities sometimes delay the decision of the water allocation as they hope for more rainfall) increases the level of uncertainty of the farmers and reduces the options farmers have to deal with the limited water availability. Studies like these have to be integrated in the optimization of the use of solar energy in large irrigation systems.

The findings of this study of the Valle Inferior irrigation system will be of interest to other large irrigation networks that use or want to use solar energy, in Spain and elsewhere. These large networks have much higher energy requirements than small, standalone solar irrigation schemes. These high energy requirements, together with irrigation being constantly available on-demand, makes it particularly challenging to match the produced solar energy to water demand. Using the results of the current study to further optimize the use of solar energy in irrigation systems can help reduce both the cost of energy for irrigation and emissions of greenhouse gases.

Besides the scenarios examined here, another promising scenario merits consideration; that is, the use of height differences to 'store' solar energy. Thus, solar energy would be used to pump water to a higher elevation reservoir during the day, with the water then allowed to flow into fields or used to generate energy (pumped hydro-energy storage) at night or at another moment of electricity demand. Implementation of such a 'hydro-battery' could also help overcome difficulties such as the inability to sell excess solar energy due to, for example, restrictions associated with the receipt of government subsidies or technical impediments to discharging solar energy to the national grid. This scenario was not explored for the Valle Inferior irrigation system as there are no significant height differences in the vicinity, making it unfeasible in this area.

Nonetheless, the use of height differences to let water flow into fields is already being done elsewhere in the Guadalquivir River Basin, at the *Canal de la Margen Izquierda del Genil* irrigation system. This irrigation system has two pumping stations that lift water to two reservoirs located some 70–100 m higher. Currently, conventional energy is used to pump water uphill at night, making use of the lower energy prices at night. In 2020, the irrigation system started making plans, together with the Guadalquivir Hydrographic Confederation, for the construction of a 9 MWp solar plant, which was expected to be completed in 2023. The objective of the project was to provide solar energy for the two pumping stations. Then, instead of pumping at night, water would be pumped uphill during the day, taking advantage of the hours in which solar energy is produced. The solar plant was expected to become the irrigation system's main energy source, covering an estimated 80 % of the total energy consumed.

Making use of height differences in irrigation systems to store solar energy could combine sustainability and economic benefits. Moreover, unlike scenarios 2 and 3 in the current research, such storage would not require farmers to change their irrigation schedule, nor would it present challenges for the energy grid. Consideration of this scenario, once again, demonstrates the complexities involved in optimizing the use of solar energy in large irrigation systems. Making use of height differences as an optimization strategy introduces new variables, such as the size of storage reservoirs, height differences between them, and influences of the pipes and turbines required to pump the water uphill and let it flow downhill. Similar to the methodology of the current study, after identifying the key variables in this scenario and their influences, optimization software can be used to find optimized solutions.

Even without their own solar plants, irrigation systems might provide pumped hydro-energy storage as a service to the national energy grid. This would be accomplished by constructing a hydro-battery at the head of an irrigation command area, and diverting the stored water either for irrigation or back to the source for restorage as needed. The economic rationale for the integration of such energy storage services by irrigation systems merits further investigation and assessment.

6. Conclusion

To tackle the high energy requirements and associated costs of irrigation, solar energy is gaining popularity in irrigation systems. However, although it is a sustainable alternative to fossil fuels, this study points to challenges that arise with the use of solar energy in large irrigation networks. In the Valle Inferior irrigation system, solar energy production exceeded the total amount of energy consumed. Nonetheless, only 52 % of the total energy consumed in the agricultural year 2020/2021 was provided by own solar production.

This study explored two solar energy optimization scenarios. One of these scenarios concerned optimizing the use of own solar energy in the system itself by adjusting irrigation schedules to only irrigate during daylight hours. However, difficulties arose, as farmers preferred irrigating at night. Another scenario concerned optimizing the economic benefits from selling solar energy, thus enabling irrigation systems to deal with higher energy prices.

A third scenario, too, was introduced but not explored empirically: the use of height differences to store solar energy in the form of potential energy. In this scenario, solar energy could be used to pump water uphill, with the energy later released during hours in which no solar energy is available or during peak hours of energy consumption. This final scenario merits further assessment and research.

The scenarios presented in this study aptly demonstrate the complexity of the challenges facing modernized irrigation systems in the energy transition age. System managers must be mindful of multiple variables, which, moreover, lead to different optimization outcomes under different operational strategies. As such, more interacting parameters need to be resolved. The different strategies also impact water delivery schedules, in some cases requiring changes in irrigation system design and in farmers' routines. This, too, should be taken into account in future decisions on optimization of solar energy in irrigation systems.

CRediT authorship contribution statement

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

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2024.120610.

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