Renewable Energy 200 (2022) 931–941

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Comparative assessment of different solar tracking systems in the optimal management of PV-operated pumping stations

Natalia Naval, Jose M. Yusta *

University of Zaragoza, Department of Electrical Engineering, C/ Maria de Luna 3, 50018, Zaragoza, Spain

ARTICLE INFO

Keywords:
Water pumping
Self-consumption
Solar tracking
Optimal management
Variable-speed pump

ABSTRACT

The integration of photovoltaic energy in pumping systems is complex, and the technical constraints of hydraulic and pumping systems must be considered. Exploitation models that link energy management with water management are necessary to ensure the profitability of these investments. This research proposes the design and application of a mathematical model for optimal hourly operation of pumping equipment at the minimum cost for a pumping station with different configurations of self-consumption photovoltaic generation for one week, subsequently extended to an entire year. The proposed optimization problem is formulated as a mixed-integer nonlinear model. Findings of this paper indicate that a self-consumption photovoltaic plant with single-axis solar tracking can increase production by 33.4% and reduce operating costs by 28.9% compared to a fixed system. Therefore, more energy is self-consumed (81.6%), and a more efficient pumping operation is achieved. The use of a two-axis tracker improves photovoltaic production by 3.2% with economic savings of 4.8% compared to a single-axis tracker, but this difference is small considering its higher investment costs and technical complexity. As a result, the single-axis solar tracker is generally used in pumping stations to achieve efficient management and reduced operating costs.

1. Introduction

Photovoltaic energy is becoming one of the most competitive alternatives to conventional energies, especially in Europe, China, and the United States. Economies of scale and innovation make photovoltaic energy the most sustainable solution for electricity production, not only from an environmental but also an economic viewpoint.

One of the main advantages of photovoltaic technology is that electricity can be produced in situ. Thus, the consumer can obtain their electricity while contributing to greater energy efficiency in the electrical system through the reduction of losses in the transmission and distribution lines. In addition, photovoltaic technology promotes employment and local economic activity with the creation of companies responsible for designing, installing, and maintaining generation facilities. In short, self-consumption contributes to a more sustainable energy model.

The advancement of solar technology together with lower prices of photovoltaic panels, as well as their improved reliability and performance, have accelerated the application of this technology to reduce energy costs in the irrigation of agricultural fields. In addition, the highest energy demands for the vast majority of crops occur from March to October, which coincides with the months of greatest solar radiation; therefore, there is a greater potential for using photovoltaic energy during this time. The economic profitability of water pumping facilities using photovoltaic generation compared to an electricity network or diesel generators is evident, but the integration of renewable energy and the pumping and hydraulic systems to which it is coupled presents great technical complexity. For example, a sudden variation in solar irradiance on cloudy days can shorten the lifespan of the mechanical and electronic components in the medium term as a result of these sudden power fluctuations. Currently, this sector employs technology allowing the implementation of robust, durable, reliable, and efficient installations.

Solar self-consumption pumping facilities can be either isolated or grid connected. However, if there was a previous connection to the grid, the consumer is better off remaining connected to the grid since it guarantees electricity supply when there is no renewable generation as well as the possibility of exporting the unconsumed surplus energy to the grid in exchange for remuneration. In this regard, the need to invest in storage systems with very high costs is also eliminated.

---

* Corresponding author.
E-mail address: jmyusta@unizar.es (J.M. Yusta).

https://doi.org/10.1016/j.renene.2022.10.007
Received 27 January 2022; Received in revised form 22 August 2022; Accepted 1 October 2022

Nomenclature

Indices

h	index for number of hours
i	index for number of fixed-speed pumps
j	index for number of variable-speed pumps

Data

$\mathrm{N_h}$	study time period
$\mathrm{N_{FP}}$	total number of fixed-speed pumps
$\mathrm{N_{VP}}$	total number of variable-speed pumps
ρ^{h}_{exp}	hourly energy sale price $\left(\frac{€}{kWh}\right)$
ρ^{h}_{imp}	hourly energy purchase price $\left(\frac{€}{kWh}\right)$
$\mathrm{P^h_{PV}}$	hourly power of photovoltaic generation (kW)
$\mathrm{P^h_{exp_{max}}}$	maximum hourly energy exported to the electricity network (kWh)
$\mathrm{P^h_{imp_{max}}}$	maximum hourly energy imported from the electricity network (kWh)
$\mathrm{V^h_{pond_{st,max}}}$	maximum volume of the water storage pond (m^3)
$\mathrm{V^h_{pond_{st,min}}}$	minimum volume of the water storage pond (m^3)
$\mathrm{Q^h_{VP_j,max}}$	maximum hourly flow of variable-speed pump j $\left(\frac{m^3}{h}\right)$
$\mathrm{Q^h_{VP_j,min}}$	minimum hourly flow of variable-speed pump j $\left(\frac{m^3}{h}\right)$
$\mathrm{Q^h_D}$	irrigation demand hourly flow $\left(\frac{m^3}{h}\right)$
$\mathrm{Q^h_{req}}$	requested hourly flow reaching the water reception pond $\left(\frac{m^3}{h}\right)$
$\mathrm{P^h_c}$	contracted power according to tariff period (kW)
$\mathrm{V^h_{pond_{rec,max}}}$	maximum volume of the water reception pond (m^3)
$\mathrm{V^h_{pond_{rec,min}}}$	minimum volume of the water reception pond (m^3)
$\mathrm{Q^h_{FP_i,rated}}$	rated flow of fixed-speed pump i in operation $\left(\frac{m^3}{h}\right)$
$\mathrm{P^h_{FP_i,rated}}$	rated power of fixed-speed pump i in operation (kW)
$\mathrm{P^h_{VP_j,max}}$	maximum power of variable-speed pump j (kW)
$\mathrm{k_{start}}$	starting cost of fixed-speed pumps i (€)
$\mathrm{k_{VP}}$	constant for variable pump power-flow ratio j

Variables

P^h_{exp}	hourly energy exported to the electricity network (kWh)
P^h_{imp}	hourly energy imported from the electricity network (kWh)
I^h_{exp}	binary variable equal to 1 if energy is exported from the pumping station; otherwise, it equals 0
I^h_{imp}	binary variable equal to 1 if energy is imported to the pumping station; otherwise, it equals 0
$I^h_{FP_i}$	binary variable equal to 1 if the fixed-speed pump i operates; otherwise, it equals 0
$I^h_{VP_j}$	binary variable equal to 1 if the variable-speed pump j operates; otherwise, it equals 0
$Q^h_{FP_i}$	hourly flow rate for fixed-speed pump i $\left(\frac{m^3}{h}\right)$
$Q^h_{VP_j}$	hourly flow rate for variable-speed pump j $\left(\frac{m^3}{h}\right)$
$Q^h_{\mathrm{pump,total}}$	total hourly flow rate of pumps $\left(\frac{m^3}{h}\right)$
$V^h_{pond_{st}}$	hourly volume of the water storage pond (m^3)
$V^h_{pond_{rec}}$	hourly volume of the water reception pond (m^3)
$P^h_{FP_i}$	power of fixed-speed pump i (kWh)
$P^h_{VP_j}$	power of variable-speed pump j (kWh)
$P^h_{\mathrm{pump,total}}$	total hourly power of pumps (kWh)
$I^h_{start_i}$	binary variable equal to 1 if pump i starts; otherwise, it equals 0
$C^h_{start_i}$	hourly starting cost of fixed-speed pumps i (€)

1.1. Literature review of photovoltaic pumping stations

There are several configurations of photovoltaic panels such as being fixed on the ground or assembled on a solar tracker, that is on movable support structures that track sun movement. The latter allow more energy to be captured by the panels by keeping them orientated perpendicularly to the sun's rays, thus increasing the hours of solar pumping. The authors of [1] review the components, types, and applications of solar tracker photovoltaic systems. The authors of [2] investigate the technical and economic performance of 1 kWp photovoltaic panels with different types of solar trackers and rotation angles. In Ref. [3], the performance of a fixed photovoltaic system with a two-axis solar tracker is compared. Based on the analysis, the photovoltaic system with the tracker obtains an average irradiation gain from 17.2 to 31.1% over fixed panels.

From the perspective of the integration of a photovoltaic facility in a pumping station, the authors of [4] examine in detail papers focusing on the components of the facility, for example the characteristics of solar panels, pumps, and tracking mechanisms, among others. Similarly, paper [5] analyzes the configuration and size of the pumping station and solar panels. Articles [6,7] evaluate the most influential parameters in the performance of the system (configuration and size of the photovoltaic plant, type and control of the pump and motor) in addition to describing the most commonly used optimization techniques. In this regard, work [8] focuses on the study of other parameters such as angle of incidence, temperature, shadows, and air mass. In Refs. [9,10], the effect of the pumping head on the efficiency of the system is analyzed. In addition, paper [10] evaluates the effect of solar radiation. The authors of [11] study performance from a technical, economic, and environmental viewpoint.

Some pumping stations have a water storage pond to optimize the management of energy generation and water resources. In these cases, the water is pumped and stored in a pond during the day using the electricity generated by its self-consumption photovoltaic facility. The stored water is used at night, on cloudy days, or when the volume of water pumped is not enough to meet water demand required by the system. Works [12,13] analyze and optimize photovoltaic facilities with storage systems for water pumping, achieving self-consumption of practically all the available energy. One article [12] evaluates the self-consumed energy based on different photovoltaic and turbine productions, while paper [13] studies two types of storage (water pond and batteries). Recently, the authors of [14] propose a model for optimal short-term operation in a real pumping station with a water storage pond and different types of pumps in addition to a self-consumption photovoltaic plant.

An important component of solar pumping is the variable frequency drive that allows the pumps to work in a range of frequencies with variable flow rates according to the needs of each moment to maximize the electrical energy collected from the panels. Work [15] selects the most appropriate pump for photovoltaic irrigation applications to run at different operating frequencies. The authors of [16] quantify energy losses for different scenarios and meteorological data (pumping water at variable frequency and direct pumping at constant power).

Regarding the mathematical techniques used to optimize the design and operation of these facilities, work [17] applies a genetic algorithm to optimize the system, including the investment cost of the photovoltaic plant and the income from the sale of crops. Other research focuses on modelling and multi-objective optimization for the sizing of a water pumping system with photovoltaic generation based on evolutionary algorithms with the application of technical and economic criteria, as do two other articles [18,19]. In addition, paper [19] includes the volume of excess water as a criterion.

Finally, articles [20–22], and [23] analyze the economic viability of different photovoltaic systems with a wide variation of powers considered for irrigation water pumping in areas such as Morocco [20], Iran [21], India [22], and the Mediterranean region [23]. In addition, work [23] analyzes different irrigation configurations both with and without variable frequency drive in the pumps as well as the use of different types of energy: renewable, diesel, and electricity from the grid. The authors of [24] compare the economic costs between the use of diesel and photovoltaic energy for irrigation pumping. Their results show that irrigation by photovoltaic energy is much more beneficial for certain crops such as soybeans, sunflowers, strawberries, etc. Another work [25] proposes a prototype in which the solar tracker system tracks sunlight in three different directions, reaching a 25% increase in efficiency.

1.2. Contribution of this article

Previous works propose simple short-term models without addressing the great challenge of the joint management of water and energy resources or the incorporation of photovoltaic self-consumption plants with different types of solar trackers for water pumping for agricultural irrigation. Therefore, in order to achieve a more complete and realistic operation model, this research proposes the development of an hourly model for optimal management of a pumping station with different types of pumps, ponds for water regulation and storage, and a self-consumption photovoltaic plant to minimize weekly operating costs for an entire year. In addition, this research can lead to more technically and economically realistic studies since it analyzes in detail the use of different configurations of photovoltaic panels for water pumping: fixed, a single north-south axis solar tracker, and a two-axis solar tracker.

The remainder of the article is presented as follows: Section 2 formulates the mathematical model for the optimal operation. Section 3 presents the case study and analyzes the results obtained from the application of the model with different types of solar trackers to an existing pumping station. Finally, Section 4 summarizes the main conclusions of this research.

2. Mathematical formulation of the technical-economic dispatch model

Sharp increases in the prices of wholesale electricity market anticipates an even more uncertain future for the energy costs of irrigation communities [26,27]. In the coming years, massive penetration of renewable energy will allow a reduction in the average price of electricity generation, although an increase in price volatility is also expected over the days, months, and years, depending on the availability of intermittent sources of electricity production [28].

In recent years, irrigation communities, thanks to favorable legislation on self-consumption, technological maturity, and the continuous reduction of the costs of solar panels, have made large investments in self-consumption photovoltaic generation facilities to improve the economic viability of their farms. It must be taken into account that the integration of photovoltaic energy in these irrigation water pumping systems is complex, and the technical constraints of the hydraulic and pumping systems must be considered. Irrigation communities generally pump water to a storage pond for further use for irrigation, which allows adequate water management. From this storage pond, the water is distributed by gravity to the irrigated fields. Pumping stations are usually equipped with several pumps, some of which incorporate a variable-speed drive to work with variable flow rates according to the required needs, allowing a more efficient pumping operation.

2.1. Literature review of dispatch models

Previous research has focused on techno-economic dispatch problems to optimize the use of available water for irrigation and the scheduling of pumping equipment at minimum operating costs.

Thus, to minimize operating costs, these models define an objective function that includes the energy consumption cost of the pumping system, maintenance costs, and/or water costs. Each model must comply with technical constraints associated with the maximum pumping capacity and maximum and minimum storage capacity.

Most of the papers reviewed express a mixed-integer linear mathematical model [29–31] with integer decision variables related to the running mode of pumps and continuous variables associated with pump parameters and/or storage capacity. These models are generally simple and do not include the characterization of different types of pumps or the joint management of water and energy resources.

Regarding solving methods, many authors use mathematical techniques to calculate the optimal operation of pumping stations and ensure convergence to an optimal solution. In addition, most calculation software incorporates efficient solvers to achieve an optimal solution for any type of problem (linear, mixed-integer, or nonlinear).

2.2. Purpose and formulation of the model

Efficient management of water infrastructures, photovoltaic generation, and electricity consumption is essential in irrigation systems. Therefore, this article aims to design and apply a new hourly model for optimal weekly management of pumping equipment according to different configurations of photovoltaic panels to meet the required water demand at the minimum operating cost at an existing pumping station (see Fig. 1) for an entire year. The self-consumption photovoltaic plant is connected to the electrical distribution network so that it can purchase energy from the electricity market at a fixed price according to the tariff periods when the photovoltaic installation itself is not able to meet the irrigation demand. In contrast, when there is excess generation, the surplus energy can be exported to the grid to gain additional income.

Next, the formulation of the proposed model is explained with the objective function, the hydraulic and electrical constraints, and the approaches considered for its development.

Equation (1) presents the objective function that seeks to minimize the operating costs of a pumping station, expressed as the difference between the system costs and the income from the sale of excess photovoltaic production. On the one hand, the costs correspond to the purchase of energy in the electricity market when photovoltaic production is not sufficient to meet demand. On the other hand, the costs of starting the pumping equipment are included to group the operating hours together, thus avoiding continuous inefficient starting and stopping. Regarding income, the sale price is only associated with the price of energy in the wholesale market.

$$\min(\mathrm{Cost}) = \sum_{\mathrm{h}=1}^{\mathrm{N_h}} \left(\rho^{\mathrm{h}}_{\mathrm{imp}} \cdot P^{h}_{imp} - \rho^{\mathrm{h}}_{\mathrm{exp}} \cdot P^{h}_{exp} + \sum_{\mathrm{i}=1}^{\mathrm{N_{FP}}} C^{h}_{start_i} \right) \tag{1}$$

Equation (2) establishes the energy balance of the system to meet the required hourly demand.

$$P^{h}_{imp} - P^{h}_{exp} = \sum_{\mathrm{i}=1}^{\mathrm{N_{FP}}} P^{h}_{FP_i} + \sum_{\mathrm{j}=1}^{\mathrm{N_{VP}}} P^{h}_{VP_j} - \mathrm{P}^{\mathrm{h}}_{\mathrm{PV}} \tag{2}$$

Equations (3)–(7) show the constraints associated with the hourly import/export of energy from and to the electricity market. Binary variables are used to make this decision and prevent import/export from occurring simultaneously. The imported hourly energy will not exceed the fixed limit of contracted power at that time, while the exported hourly energy will be less than or equal to the maximum available photovoltaic production.

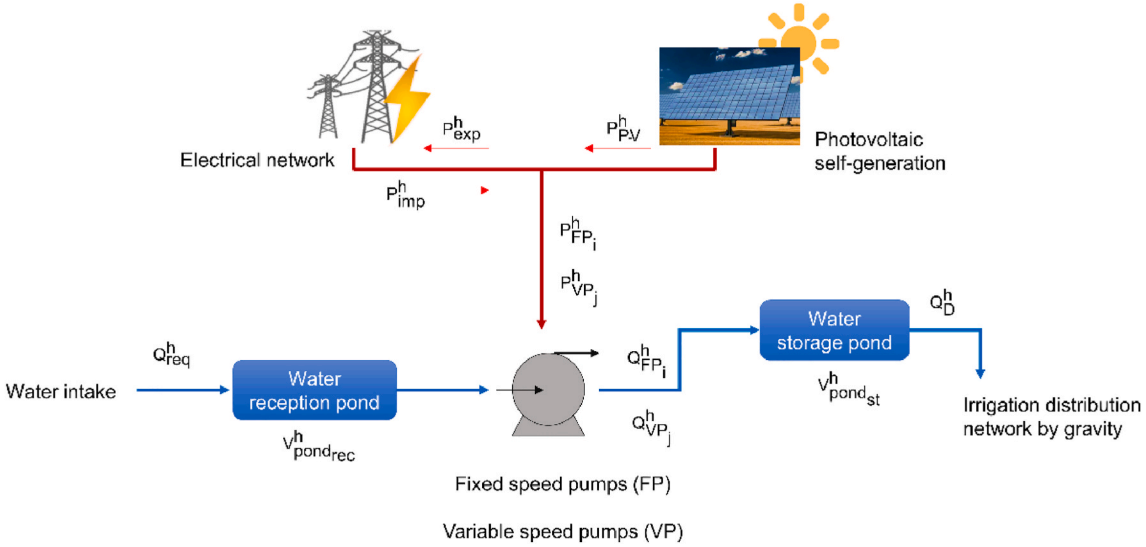


Fig. 1. Overview of the proposed management model.

$$0 \le P^h_{imp} \le \mathrm{P}^{\mathrm{h}}_{\mathrm{imp_{max}}} \cdot I^h_{imp} \tag{3}$$

$$0 \le P^h_{exp} \le \mathrm{P}^{\mathrm{h}}_{\mathrm{exp_{max}}} \cdot I^h_{exp} \tag{4}$$

$$\mathrm{P}^{\mathrm{h}}_{\mathrm{imp_{max}}} = \mathrm{P}^{\mathrm{h}}_{\mathrm{c}} \tag{5}$$

$$\mathrm{P}^{\mathrm{h}}_{\mathrm{exp_{max}}} = \mathrm{P}^{\mathrm{h}}_{\mathrm{PV}} \tag{6}$$

$$I^h_{imp} + I^h_{exp} \le 1 \tag{7}$$

Equations 8–10 characterize the behavior of the pumping equipment. On the one hand, it is assumed that fixed-speed pumps have an all-or-nothing operating mode: the pumps run at full load; when operating, their power is equal to their rated power, and when stopped, their power is 0. On the other hand, to characterize the variable-speed pumps, the affinity laws that relate the flow and power with the rotation speed are used. Flow rate is proportional to the rotation speed of the pump shaft, while the absorbed power varies with the cube of the rotation speed [32]. From these relationships, an equation is obtained that relates both variables to each other (flow rate and power) for any pump speed. It should be noted that several approaches are used for this modelling:

1. The total hydraulic head remains constant against changes in speed for two reasons:
   a. Friction losses in the pipeline are very small because the pipes of the water pumping systems for agricultural irrigation have large diameters to obtain high efficiency in the water transport and distribution system.
   b. The water reception and storage ponds have large areas to keep the height of water approximately constant.
2. The performance remains constant against changes in speed for the following reason:
   a. The Sârbu and Borza approach allows disregarding this performance variation in the case that the speed variation is less than 33% of the pump's rated speed [33].

$$P^h_{FP_i} = \mathrm{P}^{\mathrm{h}}_{\mathrm{FP_i,rated}} \cdot I^h_{FP_i} \tag{8}$$

$$P^h_{VP_j} = \mathrm{k_{VP}} \cdot \left(Q^h_{VP_j}\right)^3 \tag{9}$$

$$\mathrm{k_{VP}} = \frac{\mathrm{P_{VP_j(f_{nom})}}}{\mathrm{Q^3_{VP_j(f_{nom})}}} \tag{10}$$

Equations (11) and (12) show the starting order of the pumping equipment according to the number of pumps needed to meet the water demand.

$$I^h_{FP_{i+1}} + \left(1 - I^h_{FP_i}\right) \le 1 \tag{11}$$

$$I^h_{VP_{j+1}} + \left(1 - I^h_{VP_j}\right) \le 1 \tag{12}$$

Equations 13–15 present the limits of the water flow rates of the pumping equipment (fixed- and variable-speed pumps).

$$Q^h_{FP_i} = \mathrm{Q}^{\mathrm{h}}_{\mathrm{FP_i,rated}} \cdot I^h_{FP_i} \tag{13}$$

$$\mathrm{Q}^{\mathrm{h}}_{\mathrm{VP_j,min}} \cdot I^h_{VP_j} \le Q^h_{VP_j} \le \mathrm{Q}^{\mathrm{h}}_{\mathrm{VP_j,max}} \cdot I^h_{VP_j} \tag{14}$$

$$Q^h_{pump,total} = \sum_{\mathrm{i=1}}^{\mathrm{N_{FP}}} Q^h_{FP_i} + \sum_{\mathrm{j=1}}^{\mathrm{N_{VP}}} Q^h_{VP_j} \tag{15}$$

Equations 16–20 show the constraints associated with the water reception pond and the water storage pond. Equations 16 and 17 determine the hourly water level in each of the ponds, while Equations 18 and 19 impose the limits associated with their capacities. Equation (20) establishes that the available volume of the storage pond at the beginning must coincide with the available volume at the end of the study period.

$$V^h_{pond_{rec}} = \mathrm{V}^{\mathrm{h-1}}_{\mathrm{pond_{rec}}} + \mathrm{Q}^{\mathrm{h}}_{\mathrm{req}} - Q^h_{pump,total} \tag{16}$$

$$V^h_{pond_{st}} = \mathrm{V}^{\mathrm{h-1}}_{\mathrm{pond_{st}}} - \mathrm{Q}^{\mathrm{h}}_{\mathrm{D}} + Q^h_{pump,total} \tag{17}$$

$$\mathrm{V}^{\mathrm{h}}_{\mathrm{pond_{rec,min}}} \le V^h_{pond_{rec}} \le \mathrm{V}^{\mathrm{h}}_{\mathrm{pond_{rec,max}}} \tag{18}$$

$$\mathrm{V}^{\mathrm{h}}_{\mathrm{pond_{st,min}}} \le V^h_{pond_{st}} \le \mathrm{V}^{\mathrm{h}}_{\mathrm{pond_{st,max}}} \tag{19}$$

$$\mathrm{V}^{\mathrm{h}}_{\mathrm{pond_{st}}}(0) = \mathrm{V}^{\mathrm{h}}_{\mathrm{pond_{st}}}(\mathrm{N_h}) \tag{20}$$

Equations (21) and (22) calculate the constraints related to the starting costs of fixed-speed pumps since as previously mentioned, irregular operation of the pumping equipment can result in inefficient operation and reduce the lifespan of the equipment. The use of a binary variable is necessary to decide whether the fixed-speed pumps start each hour and thus take into account their corresponding cost. The constant $\mathrm{k_{start}}$ represents the starting cost of a pump.

$$C^{h}_{start_i} = \mathrm{k}_{\mathrm{start}} \cdot I^{h}_{start_i} \tag{21}$$

$$\left(I^{h}_{FP_i} - I^{h-1}_{FP_i}\right) \le I^{h}_{start_i} \tag{22}$$

According to the equations of the model, the proposed problem constitutes a mixed-integer nonlinear optimization model (MINLP) that determines the technical-economic hourly dispatch of a pumping station. The solution reflects the optimal hourly management of the pumps and the water reception and storage ponds according to different configurations of the photovoltaic panels (fixed, single north-south axis tracker, and two-axis tracker). To better illustrate the behavior of the model, it should be noted that the optimization problem is solved separately every hour for a week, and the decision-making process is progressively repeated for the 52 weeks of an entire year.

This MINLP problem is solved by GAMS software (General Algebraic Modelling System) by applying branch-and-cut techniques to divide the nonlinear model into a list of subproblems that facilitate obtaining an optimal solution. The execution time was 168 h, and a computer with an Intel® Core i7 processor, 3.00 GHz CPU, and 16 GB of RAM was used.

3. Analysis of results

3.1. Description of the case study

Photovoltaic pumping systems for irrigation are growing in recent years to reduce dependence on electrical grids. Globally, most pumping stations are located in India, Iran, Brazil, Spain, among others [34]. These sites have large water needs as well as a huge solar potential. The average solar radiation value in these countries is around 4 kWh/m^2 per day [35]. It should be noted that the periods of greatest water demand coincide with the periods of greatest solar radiation. As a result, the authors chose a pumping system in Spain due to the high potential of solar energy and the availability of the technical specifications of the main components of the system. Thus, the real techno-economic scope of the joint management of water and energy resources integrated in a pumping station with different configurations of self-consumption photovoltaic generation is analyzed.

The model proposed in Section 2 is tested with real data from a pumping system with photovoltaic self-consumption formed by different energy and water infrastructures that provide irrigation services to an area of 2751 ha of crops through two water ponds and a water pumping station in the province of Huesca, Spain [14] (see Fig. 2). This site (latitude: 41.855° and longitude: 0.390°) has a great potential for solar radiation, which is within the range of 1691.4 kWh/m^2 to 2024.4 kWh/m^2 per year, received on a tilt PV surface [35].

Fig. 2. Water pumping system.

Electricity consumption is seasonal, being very high in the months of the irrigation season from May to September. In 2019, this pumping station recorded an annual electricity consumption of 2729 MWh and water consumption of 25.42 hm^3. Fig. 3 represents the volume of water pumped in this irrigation system on a monthly basis; it illustrates greater demand in the months of irrigation season.

Table 1 presents the most relevant technical data for the pumping station. It is composed of five pumps in parallel, which allows the progressive entry of different pumps for a water supply that varies according to demand. In irrigation pumping facilities, it is common to operate at a frequency equal to or greater than 35 Hz to avoid pressure drops in the pumping equipment. The study's system has two water ponds: 1) a lower pond (reception pond) fed by communicating vessels of the nearest water transport channel and from which the pumping station draws water, and 2) an upper pond (storage pond) to which water is pumped. For a more detailed technical and economic description of the study facility, work [14] can be consulted.

The pumping system also has a self-consumption photovoltaic generation plant connected to the grid with an installed power of 1.5 MW. Fig. 4 shows a comparison of photovoltaic production according to the main configurations of the photovoltaic panels. The incorporation of the system with single-axis solar tracking increases photovoltaic production by 33.4% compared to a fixed system.

3.2. Results

3.2.1. Definition of scenarios

The proposed optimal hourly technical-economic management model (MINLP) seeks to minimize the weekly operating costs of a pumping station with a self-consumption photovoltaic plant connected to the grid with different configurations of solar panels throughout the entire year. This research offers a detailed comparison of the optimal hourly management obtained from the pumping equipment and the water reception and storage ponds with the three configurations used for the photovoltaic modules (fixed system, single north-south axis solar tracking, and two-axis solar tracking). In addition, the case without photovoltaic self-consumption is initially calculated in order to analyze further benefits of photovoltaic generation.

Case 0. No photovoltaic self-consumption

Case 1. Fixed photovoltaic modules

Case 2. Photovoltaic modules with one-axis tracker

Case 3. Photovoltaic modules with two-axis tracker

Water demand is the key variable that determines the profitability of a photovoltaic system for agricultural irrigation. The more solar resources used, the greater the profitability of the facility. In general, the more sunlight there is, the more water a crop needs, but there is also a greater amount of photovoltaic energy available for water pumping. Conversely, during cloudy or rainy days, the production of electricity from solar panels will be low or even null, but the evapotranspiration of the crops will also be low. It should be noted that the factor that influences evapotranspiration even more than temperature is solar irradiance. For this reason, there is a positive correlation between pumping through photovoltaic generation and water needs since, on a cloudy day, although it is not possible to irrigate, evapotranspiration, and therefore water loss, is also minimal.

3.2.2. Monthly analysis

Tables 2 and 3 summarize the optimal monthly results for energy and water, respectively.

The variable-speed drive is an essential component for water

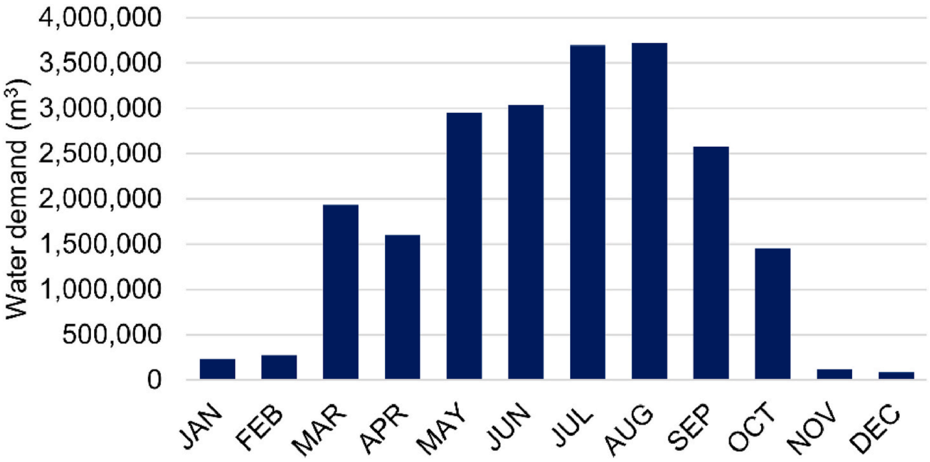


Fig. 3. Monthly volume of water required for pumping.

Table 1
Technical data of the pumping station.

	PUMPS		WATER PONDS	
Type	Fixed-speed	Variable-speed	Reception	Storage
Number	4	1	1	1
Rated power at 50 Hz (kW)	400	400	–	–
Rated flow at 50 Hz (m^3/h)	1967	1967	–	–
Minimum power at 35 Hz (kW)	–	137.2	–	–
Minimum flow rate at 35 Hz (m^3/h)	–	1377	–	–
Minimum volume (m^3)	–	–	75,000	200,000
Maximum volume (m^3)	–	–	155,000	280,000

pumping by photovoltaic generation since it varies the rotational speed of the pump motor by modifying the power frequency, and in this way, it modifies the characteristic curve of the pump, adapting it to the available solar production. This method of regulating the pumping equipment provides energy savings since no additional losses are introduced.

Thanks to the solar tracker, the pump can run more hours per day and supply a higher flow throughout the day. In addition, the use of variable-frequency drives reduces the frequency in hours that the rated power of the motor is not reached and thus extends the pumping time, even if not at rated flow.

The number of fixed-speed pumps in operation varies according to irrigation demand, and their operating hours are synchronized to improve pumping efficiency and avoid successive starts and stops. Doing this has two important drawbacks: reduction in the lifespan of the pumping equipment and higher electricity consumption.

Cases 2 and 3 included the incorporation of one-axis and two-axis solar trackers, respectively. It is possible to increase the photovoltaic self-consumption in all months of the year with respect to Case 1 (fixed system). As a result, the amount of energy imported from the grid necessary to meet demand is reduced, and the reception and storage pond levels are within the capacity limits. However, the energy improvement is not as important when changing from single-to double-axis trackers. In Case 3 (two-axis tracker), the energy exported to the grid is greater than that in Case 2 (one-axis tracker) because by slightly increasing the photovoltaic production, there are more hours in which the minimum power of the variable-speed pump is not reached (137.2 kW). In addition, there are more hours in which the storage pond reaches its maximum capacity and cannot pump more water through the photovoltaic plant. As a consequence, the self-consumption ratio is slightly affected.

The model tends to seek an optimal value of self-consumed photovoltaic energy by virtue of which the model manages the optimal operation of the system at minimum cost. It should be noted that the model must always meet the required water demand; thus, if generation with solar panels is insufficient, the system purchases energy from the

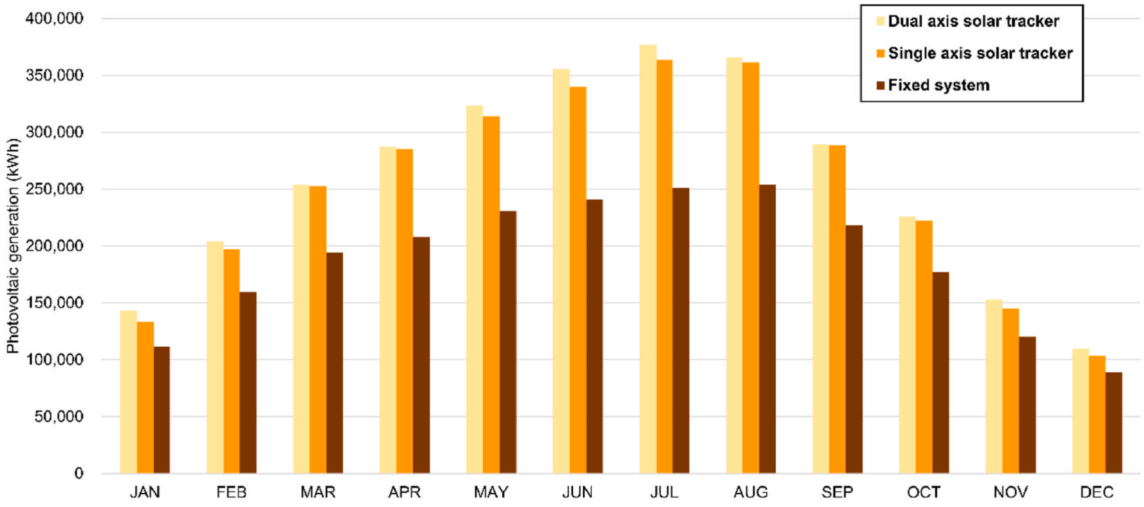


Fig. 4. Monthly photovoltaic production with the three configurations studied.

Table 2
Optimal monthly energy results for the four case studies.

Month	Case	P_{PV} (kWh)	P_{exp} (kWh)	P_{imp} (kWh)	% P_{self}	P_{FP} (kWh)	P_{VP} (kWh)	$P_{pump,\ total}$ (kWh)	Δ P_{PV}	Δ P_{exp}	Δ P_{imp}
JAN	0	–	–	24,380	–	0	24,380	24,380	–	–	0%
	1	99,049	91,038	16,488	8.09%	0	24,499	24,499	0%	0%	−32%
	2	110,896	64,856	0	41.52%	37,200	8839	46,039	12%	−29%	−100%
	3	117,234	71,195	0	39.27%	38,971	7068	46,039	18%	−22%	−100%
FEB	0	–	–	28,254	–	0	28,254	28,254	–	–	0%
	1	247,092	222,752	6608	9.85%	0	30,948	30,948	0%	0%	−76%
	2	253,251	200,525	2334	20.82%	35,200	19,859	55,059	2%	−10%	−92%
	3	260,645	207,920	2334	20.23%	35,200	19,859	55,059	5%	−7%	−92%
MAR	0	–	–	337,829	–	283,429	54,400	337,829	–	–	0%
	1	150,430	20,456	206,309	86.40%	191,314	144,978	336,292	0%	0%	38%
	2	260,634	2960	103,905	98.86%	267,486	94,094	361,580	73%	−86%	−69%
	3	260,947	2926	85,608	98.88%	249,771	93,858	343,629	73%	−86%	−75%
APR	0	–	–	271,439	–	219,429	52,010	271,439	–	–	0%
	1	194,579	16,893	73,369	91.32%	142,286	108,770	251,056	0%	0%	−73%
	2	243,397	2194	36,078	99.10%	178,286	98,995	277,280	25%	−87%	−87%
	3	261,093	9644	38,627	96.31%	190,286	99,116	289,402	34%	−43%	−86%
MAY	0	–	–	545,982	–	490,686	55,296	545,982	–	–	0%
	1	264,644	17,985	293,587	93.20%	398,571	141,674	540,246	0%	0%	−46%
	2	296,155	542	240,009	99.82%	434,000	101,622	535,622	12%	−97%	−56%
	3	306,267	1220	249,133	99.60%	432,229	121,952	554,181	16%	−93%	−54%
JUN	0	–	–	566,909	–	507,428	59,481	566,909	–	–	0%
	1	203,850	23,319	356,717	88.56%	450,857	86,383	537,240	0%	0%	−37%
	2	355,328	992	217,285	99.72%	428,571	143,050	571,621	29%	−78%	−62%
	3	372,797	3374	183,201	99.09%	445,714	106,909	552,624	36%	−25%	−68%
JUL	0	–	–	635,525	–	538,514	97,011	635,525	–	–	0%
	1	232,074	1369	460,168	99.41%	540,286	150,587	690,873	0%	0%	−28%
	2	385,382	236	292,508	99.94%	558,000	119,655	677,655	66%	−83%	−54%
	3	396,433	483	330,534	99.88%	559,771	166,712	726,484	71%	−65%	−48%
AUG	0	–	–	650,613	–	547,371	103,242	650,613	–	–	0%
	1	252,369	2051	401,697	99.19%	545,600	106,419	652,019	0%	0%	−38%
	2	381,813	1831	312,497	99.52%	575,714	116,765	692,479	51%	−11%	−51%
	3	389,557	2410	310,522	99.38%	575,714	121,954	697,668	54%	18%	−52%
SEP	0	–	–	470,446	–	418,286	52,160	470,446	–	–	0%
	1	198,524	2487	263,836	98.75%	332,571	127,301	459,872	0%	0%	−43%
	2	297,285	1012	211,770	99.66%	411,429	96,615	508,043	50%	−59%	−55%
	3	297,285	3831	163,915	98.71%	358,286	99,549	457,834	50%	54%	−65%
OCT	0	–	–	250,070	–	205,485	44,585	250,070	–	–	0%
	1	220,016	92,194	96,689	58.10%	145,257	79,254	224,512	0%	0%	−61%
	2	222,859	9570	60,290	95.71%	200,171	73,406	273,578	1%	−90%	−76%
	3	225,734	9618	46,205	95.74%	193,086	69,235	262,320	3%	−90%	−81%
NOV	0	–	–	12,361	–	0	12,361	12,361	–	–	0%
	1	162,413	153,838	11,537	5.28%	12,000	8112	20,112	0%	0%	−6%
	2	209,311	188,740	2126	9.83%	12,000	10,697	22,697	29%	23%	−83%
	3	224,069	203,498	2126	9.18%	10,286	12,412	22,697	38%	32%	−83%
DEC	0	–	–	9500	–	0	9500	9500	–	–	0%
	1	115,006	104,258	4924	9.35%	0	15,672	15,672	0%	0%	−48%
	2	115,657	102,354	2547	11.50%	3543	12,308	15,850	1%	−2%	−73%
	3	123,885	110,334	2397	10.94%	3543	12,405	15,948	8%	6%	−75%

electricity market to satisfy the demand.

However, in the winter months, that is in the months outside the irrigation season, all the photovoltaic energy produced is sold to the grid, and thus the system receives income (see Table 2). Another situation in which the system exports energy to the grid is when the available photovoltaic generation is less than the minimum power capable of absorbing the variable-speed pump.

3.2.3. *Analysis of a week of peak demand*

Fig. 5 represents the optimal operation for one week in July according to the type of solar tracking system studied: fixed (Fig. 5a), one-axis tracker (Fig. 5b), and two-axis tracker (Fig. 5c). July is the month of greatest water demand for almost all crops as well as the month of greatest insolation (Fig. 5d). In all cases studied, the system imports energy from the grid in the hours of lowest energy cost to meet the necessary demand for irrigation. In addition, thanks to the variable-speed drive, the system exploits solar production and connects its pumps during daytime periods of high solar radiation to store water and ensure the possibility of being able to irrigate on cloudy or rainy days with low or no solar radiation. Agricultural irrigation occurs at night mainly to reduce evaporation losses. Consequently, at night, the storage pond decreases in volume to satisfy the irrigation demand, while in the daytime, its volume increases through pumping via the solar panels.

For Cases 2 and 3 with solar tracking, the energy purchased from the electricity market is lower than in Case 1 (fixed system) since by increasing photovoltaic production by 66.05% and 70.82%, respectively, the system can self-consume more energy. It is not necessary to import as much energy from the grid (reductions of 36% and 28%, respectively) to satisfy the required demand and meet the other electrical and hydraulic constraints imposed on the model.

Regarding photovoltaic production curves, the incorporation of the solar tracker flattens the production curve since it allows extension of the maximum power time and thus produces a greater capacity for more hours per day (see Fig. 5). The one-axis solar tracker (Case 2) moves east to west as the day goes by, while the two-axis solar tracker (Case 3) modifies both the direction of the axis and its angle with respect to the earth. Therefore, this type of module is oriented directly to the sun throughout the year. The curves for Cases 2 and 3 are similar because in Case 2, the tracker has a slight inclination to the south since this practice is common to achieve a flatter curve. If it were completely horizontal,

Table 3
Optimal monthly water results for the four case studies.

Month	Case	Q_{FP} (m^3)	Q_{VP} (m^3)	$V_{pond_{rec}}$ (avg) (m^3)	$V_{pond_{st}}$ (avg) (m^3)
JAN	0	0	235,954	141,162	213,838
	1	0	235,954	139,194	215,806
	2	182,931	53,023	130,393	224,607
	3	191,642	44,312	132,398	222,602
FEB	0	0	278,080	151,068	203,932
	1	0	278,080	149,704	205,296
	2	173,096	104,984	148,082	206,918
	3	173,096	104,984	146,658	208,342
MAR	0	1,393,760	539,700	138,242	216,758
	1	940,788	992,673	130,737	224,263
	2	1,315,361	618,099	124,442	230,558
	3	1,228,251	705,209	127,761	227,239
APR	0	1,079,040	520,183	130,229	224,771
	1	699,690	899,533	113,762	241,238
	2	876,720	722,503	116,475	238,525
	3	935,730	663,493	116,423	238,577
MAY	0	2,412,947	542,646	138,436	216,564
	1	1,959,975	995,618	130,032	224,968
	2	2,134,195	821,398	114,262	240,738
	3	2,125,484	830,109	112,609	242,391
JUN	0	2,495,280	543,737	142,300	212,700
	1	2,217,090	821,927	123,311	231,689
	2	2,107,500	931,517	124,976	230,024
	3	2,191,800	847,217	126,028	228,972
JUL	0	3,054,538	639,953	141,848	213,916
	1	2,656,855	1,037,636	124,395	230,605
	2	2,743,965	950,526	121,682	233,318
	3	2,752,676	941,815	125,385	229,615
AUG	0	2,691,699	1,028,301	119,770	235,230
	1	2,682,988	1,037,012	118,084	236,916
	2	2,831,075	888,925	124,155	230,845
	3	2,831,075	888,925	119,847	235,153
SEP	0	2,056,920	520,680	141,364	213,636
	1	1,635,420	942,180	127,021	227,979
	2	2,023,200	554,400	125,691	229,309
	3	1,761,870	815,730	119,357	235,643
OCT	0	1,010,476	445,903	134,206	220,794
	1	714,302	742,078	135,834	219,166
	2	984,343	472,037	112,727	242,273
	3	949,499	506,881	114,580	240,420
NOV	0	0	120,000	151,633	203,367
	1	59,010	60,990	149,915	205,085
	2	59,010	60,990	150,665	204,335
	3	50,580	69,420	151,511	203,489
DEC	0	0	88,571	153,146	201,854
	1	0	88,571	152,693	202,307
	2	17,422	71,149	153,006	201,994
	3	17,422	71,149	153,067	201,933

there would be a slight decrease in irradiance at noon due to the geometry of the tracker movement.

3.2.4. Annual analysis

During the winter months, when the demand for irrigation is very low, the demand can be met with only photovoltaic generation for cases with solar tracking without needing to purchase energy from the electricity market (see Fig. 6). In addition, the electricity generation potential of the self-consumption photovoltaic plant can be used to export surpluses of energy to the distribution network and consequently obtain income from its sale. It should be noted that the photovoltaic energy source is always the main and priority source to satisfy the demand, and in the daytime hours with solar radiation, the pumps provide the system with the volume of water that they are capable of pumping. The grid is only used in a specific and complementary manner in periods of high irrigation demand, corresponding mainly to the summer months when the available photovoltaic energy is insufficient to meet demand. In addition, this study's system has a six-period high voltage tariff contracted, but the grid is only available in the cheapest tariff period associated with night hours and weekends since in the other periods with higher energy costs, the system has a minimum contracted power and cannot incur penalties for excess power.

Table 4 shows the optimal annual results for the four case studies. Regardless of the solar system configuration used, the installation of a photovoltaic self-consumption plant increases pumping hours during daytime hours and reduces costs of the pumping station, by decreasing the amount of energy imported from the grid to meet the weekly water demand. Case 1 reduces the annual sum of energy purchased from the grid by 42.36% compared to Case 0, while Cases 2 and 3 reduce it by 61.05% and 62.81%, respectively. Case 0 uses mostly fixed speed pumps as it needs to buy all the energy in the electricity market during the night hours and weekends with lower energy cost to meet the irrigation demand. Nevertheless, the cost per volume of water pumped is the highest compared to the rest of the cases studied since there is no photovoltaic energy support in this case.

Cases 2 and 3 achieve a higher self-consumption ratio (81.62% and 80.64%, respectively) since the solar tracker increases the energy captured by the panels by maintaining a more perpendicular orientation to the sun's rays. In Case 3 with a two-axis solar tracker, self-consumption is slightly lower than with the one-axis system. This is due to the increase in exported energy when production increases as a consequence of the storage pond being at full capacity for a greater number of hours, and on a greater number of occasions, the minimum power of the variable-speed pump is not reached through using more fixed-speed pumps.

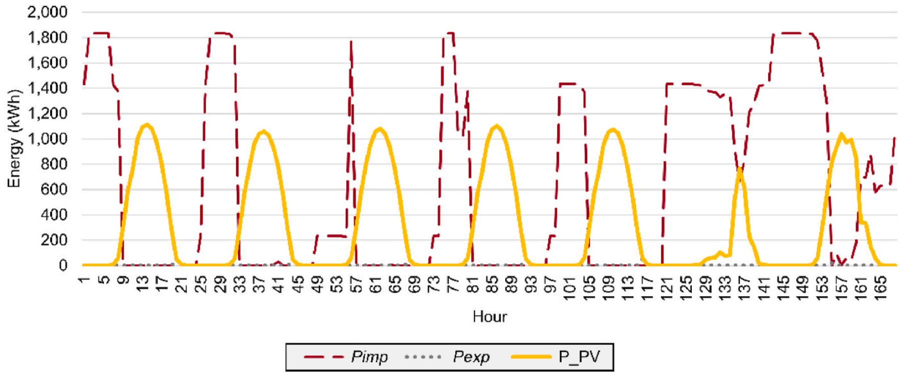
It is common to include the ratios of energy consumed per volume of water and the cost per volume of water in profitability studies of water pumping facilities for agricultural irrigation. Cases 2 and 3 obtain a higher and similar ratio of energy consumed per volume of water (0.158 kWh/m^3) since by using a solar tracker, thus exploiting greater solar radiation, the number of fixed-speed pumps is greater than in Case 1; therefore, there is higher energy consumption. Regarding the cost per volume of water pumped, Case 3 obtains the lowest ratio (0.0033 €/m^3) since the use of a two-axis solar tracker maximizes the solar energy captured and thus increases water pumped during daytime hours and reduces the need to purchase energy from the electricity market.

4. Discussion

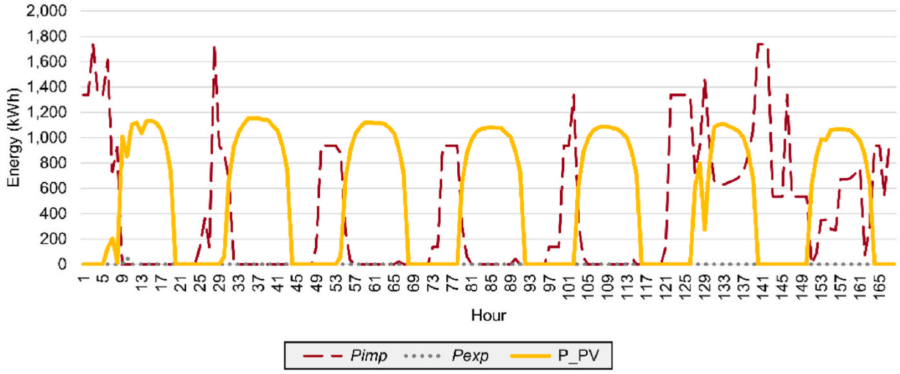
From the analysis of the results, it can be verified that it is always more profitable to maximize the self-consumption of photovoltaic energy due to the savings obtained by the system when it stops consuming energy from the grid to pump water for agricultural irrigation. The costs avoided include the cost of electricity generation on the wholesale electricity market as well as fees for the use of electricity networks and taxes. However, the additional income from the sale of surplus photovoltaic generation is only valued at the price set by the wholesale electricity market.

As a result of a lower purchase of electricity from the grid, the pumping station with fixed photovoltaic modules (Case 1) achieves a 44.87% reduction in annual costs compared to the situation without a PV self-consumption system (Case 0). This percentage is higher in Cases 2 and 3 with solar tracking, reaching 60.84% for the 1-axis system and 62.75% for the 2-axis one. From the results obtained, it is verified that the proposed mathematical dispatch model with photovoltaic generation allows a reduction of the operating costs of the irrigation water pumping system by maximizing photovoltaic self-consumption.

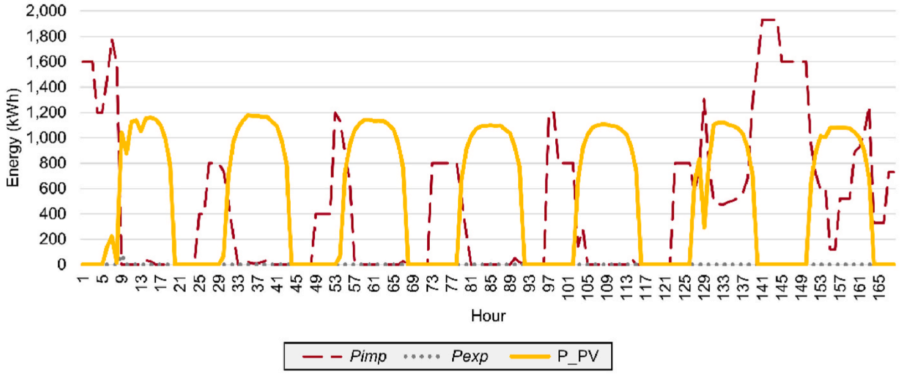
The pumping station with solar tracking can increase self-consumption annually by 20% compared to a fixed system (Case 1), while the difference between the one-axis (Case 2) and two-axis (Case 3) systems is negligible. Solar tracking systems allow a flatter production curve, thus exploiting more hours of solar radiation for pumping and reducing the need to purchase energy from the electricity market (−32.42%/−35.46% annually with respect to a fixed system if a one-axis/two-axis tracker is used, respectively) to satisfy the irrigation demand.



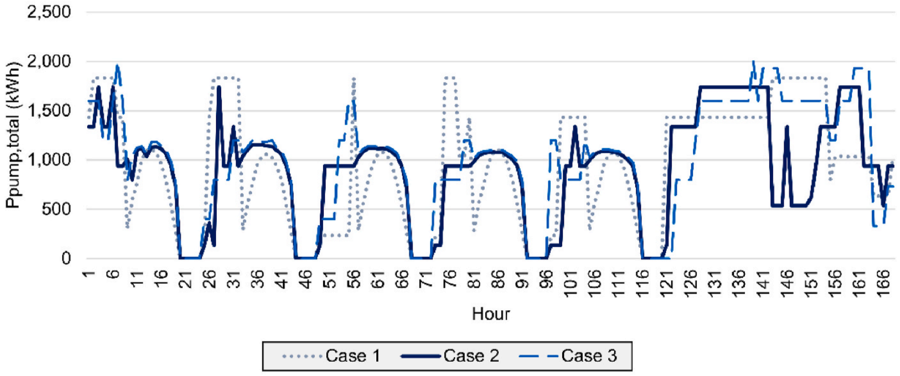
a) Photovoltaic generation, exported energy and electricity consumption from the grid for case 1: Fixed system



b) Photovoltaic generation, exported energy and electricity consumption from the grid for case 2: Single axis solar tracker



c) Photovoltaic generation, exported energy and electricity consumption from the grid for case 3: Dual axis solar tracker



d) Electricity demand for pumping in the three case studies

Fig. 5. Optimal hourly energy results for the three case studies with photovoltaic generation in July.

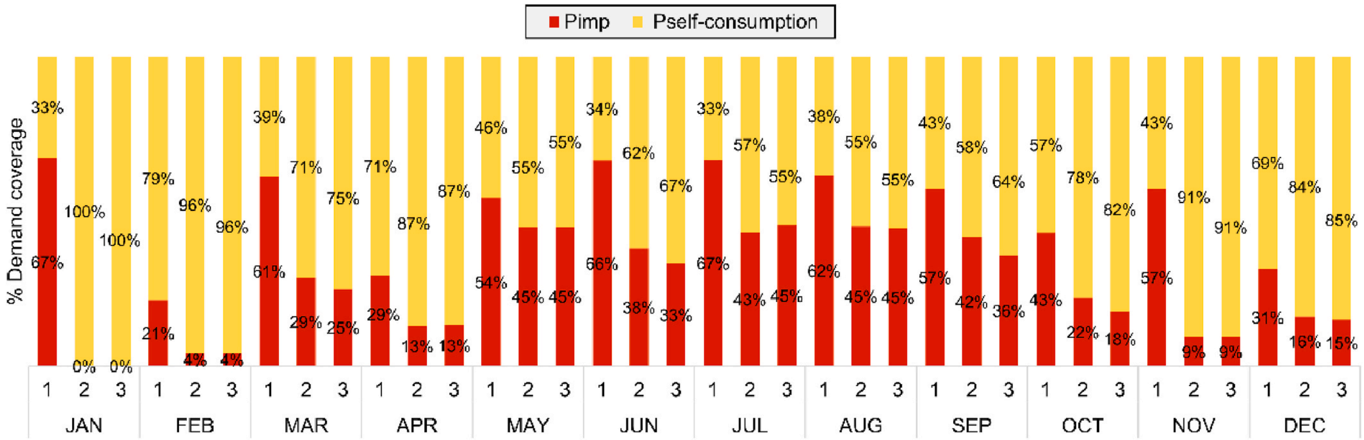


Fig. 6. Monthly distribution of demand coverage with photovoltaic generation and electricity from the grid for the three case studies.

Table 4
Annual results for the four case studies.

	Case 0	Case 1	Case 2	Case 3
$Q_{\text{pump, total}}$ (m^3)	25,418,371	25,418,371	25,418,371	25,418,371
$P_{\text{pump, total}}$ (kWh)	3,803,312	3,783,340	4,037,505	4,023,886
P_{PV} (kWh)	–	2,340,045	3,131,968	3,235,945
P_{imp} (kWh)	3,803,312	2,191,929	1,481,349	1,414,602
P_{exp} (kWh)	–	748,638	575,812	626,452
$P_{\text{self-consumption}}$ (%)	–	68.01	81.62	80.64
Ratio kWh/m^3	0.150	0.148	0.158	0.158
Total cost (€)	225,916	124,533	88,461	84,137
Total income (€)	–	36,203	29,143	31,667
Ratio €/m^3	0.0089	0.0049	0.0035	0.0033

The two-axis tracking system (Case 3) is a more complex system that requires more site preparation, more space to avoid shading between PV modules, additional strip excavations for cabling, and also some additional elevation. As a consequence, these installations have a higher investment and maintenance cost as well as a higher construction complexity since they have two degrees of freedom to perfectly align the photovoltaic panels perpendicular to the sun's rays. Work [36] analyzes the economic profitability of PV systems with different configurations (fixed and solar tracker). That paper considered that the investment cost of dual-tracker solar systems is more than double the investment cost of the fixed system, while the cost of the single-axis tracker system increases by 22%.

There are reviews that verify the production increase of PV systems with solar trackers [3,37]. Those publications obtain an improvement ratio from 17% to 40%. Our paper shows that the pumping station analyzed with a single-axis solar tracker (Case 2) increases the energy produced by 33.4% compared to a fixed system (Case 1), that is, within the range observed in the literature. The two-axis tracking system is unprofitable compared to the small increase obtained in energy produced with respect to the single-axis tracking system (4.44% additional).

For these reasons, water pumping systems generally opt for the installation of photovoltaic modules with single-axis solar tracking (Case 2) by balancing the cost of adding tracking structures with the increase in energy production. The availability of a flatter production curve in single-axis solar tracking is also a great improvement for better operation of pumping facilities compared to fixed systems.

5. Conclusions

The adequate integration of self-consumption photovoltaic plants in water pumping systems presents a great challenge for irrigation since it must include the perfect coupling of a renewable generation system and a hydraulic and pumping system. This paper proposes the development of a mathematical model that minimizes the weekly operating costs of a pumping station through optimal hourly management of pumping equipment, water infrastructures, and a self-consumption photovoltaic generation plant connected to the grid to satisfy the demand required for irrigation. The optimization process is repeated for the 52 weeks of an entire year.

To validate the model, the authors applied it to an existing pumping system with different configurations of solar panels to obtain a detailed technical and economic analysis of the integration of self-consumption photovoltaic plants. The most interesting findings of this research are as follows:

- The proposed mathematical model always tends to exploit the available photovoltaic production to meet irrigation needs and therefore works to minimize the operating costs of the pumping station. If necessary, the model uses the electrical grid as an auxiliary source to satisfy the water demand for irrigation at all times.
- Solar tracking systems improve the way in which the output power is delivered. Maximum power is reached practically from the first hour of the morning so that the production remains almost constant until late in the afternoon. As a result, this system improves the operation of the pumping system, yielding a more stable operation with fewer fluctuations in the variable frequency drive.
- The best selection of solar panels for pumping stations is the single-axis tracker since the dual-axis tracker only provides a 3.2% increase in energy production, while investment cost and technical complexity are significantly higher.

In short, this research can help improve the design and operation of pumping stations with grid-connected photovoltaic plants. The integration of electricity production to the pumping and storage hydraulic facilities, so critical in these systems, can lead to more complete and realistic studies from technical and economic viewpoints. In addition, this approach can become a very useful tool for selecting the most suitable configurations for solar panels according to site characteristics and technical conditions of the water pumping system.

CRediT authorship contribution statement

Natalia Naval: Conceptualization, Methodology, Software, Formal analysis, Writing – original draft, Writing – review & editing. **Jose M. Yusta:** Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing, Supervision, Funding acquisition.

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.

References

[1] A.Z. Hafez, A.M. Yousef, N.M. Harag, Solar tracking systems: technologies and trackers drive types – a review, Renew. Sustain. Energy Rev. 91 (June 2017) (2018) 754–782, https://doi.org/10.1016/j.rser.2018.03.094.

[2] A. Bahrami, C.O. Okoye, The performance and ranking pattern of PV systems incorporated with solar trackers in the northern hemisphere, Renew. Sustain. Energy Rev. 97 (August) (2018) 138–151, https://doi.org/10.1016/j.rser.2018.08.035.

[3] F.M. Hoffmann, R.F. Molz, J.V. Kothe, E.O.B. Nara, L.P.C. Tedesco, Monthly profile analysis based on a two-axis solar tracker proposal for photovoltaic panels, Renew. Energy 115 (2018) 750–759, https://doi.org/10.1016/j.renene.2017.08.079.

[4] V.C. Sontake, V.R. Kalamkar, Solar photovoltaic water pumping system - a comprehensive review, Renew. Sustain. Energy Rev. 59 (2016) 1038–1067, https://doi.org/10.1016/j.rser.2016.01.021.

[5] M. Aliyu, G. Hassan, S.A. Said, M.U. Siddiqui, A.T. Alawami, I.M. Elamin, A review of solar-powered water pumping systems, Renew. Sustain. Energy Rev. 87 (2018) 61–76.

[6] S.S. Chandel, M. Nagaraju Naik, R. Chandel, Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies, Renew. Sustain. Energy Rev. 49 (2015) 1084–1099, https://doi.org/10.1016/j.rser.2015.04.083.

[7] G. Li, Y. Jin, M.W. Akram, X. Chen, Research and current status of the solar photovoltaic water pumping system – a review, Renew. Sustain. Energy Rev. 79 (2017) 440–458, https://doi.org/10.1016/j.rser.2017.05.055.

[8] M. Hadwan, A. Alkholidi, Assessment of factors influencing the sustainable performance of photovoltaic water pumping systems, Renew. Sustain. Energy Rev. 92 (October 2017) (2018) 307–318, https://doi.org/10.1016/j.rser.2018.04.092.

[9] M. Benghanem, K.O. Daffallah, S.N. Alamri, A.A. Joraid, Effect of pumping head on solar water pumping system, Energy Convers. Manag. 77 (2014) 334–339, https://doi.org/10.1016/j.enconman.2013.09.043.

[10] A.K. Tiwari, V.R. Kalamkar, Effects of total head and solar radiation on the performance of solar water pumping system, Renew. Energy 118 (2018) 919–927, https://doi.org/10.1016/j.renene.2017.11.004.

[11] A. Nikzad, M. Chahartaghi, M.H. Ahmadi, Technical, economic, and environmental modeling of solar water pump for irrigation of rice in Mazandaran province in Iran: a case study, J. Clean. Prod. 239 (2019), 118007, https://doi.org/10.1016/j.jclepro.2019.118007.

[12] M. Petrollese, P. Seche, D. Cocco, Analysis and optimization of solar-pumped hydro storage systems integrated in water supply networks, Energy 189 (2019), https://doi.org/10.1016/j.energy.2019.116176.

[13] M. Zamanlou, M.T. Iqbal, Design and analysis of solar water pumping with storage for irrigation in Iran, in: 2020 IEEE 17th Int. Conf. Smart Communities Improv. Qual. Life Using ICT, *IoT AI*, 2021, pp. 118–124, https://doi.org/10.1109/honet50430.2020.9322660.

[14] N. Naval, J.M. Yusta, Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation, J. Clean. Prod. 316 (2021), 128386, https://doi.org/10.1016/j.jclepro.2021.128386.

[15] R.H. Almeida, J.R. Ledesma, I.B. Carrêlo, L. Narvarte, G. Ferrara, L. Antipodi, A new pump selection method for large-power PV irrigation systems at a variable frequency, Energy Convers. Manag. 174 (2018) 874–885, https://doi.org/10.1016/j.enconman.2018.08.071.

[16] L. Narvarte, R.H. Almeida, I.B. Carrêlo, L. Rodríguez, L.M. Carrasco, F. Martinez-Moreno, On the number of PV modules in series for large-power irrigation systems, Energy Convers. Manag. 186 (2019) 516–525, https://doi.org/10.1016/j.enconman.2019.03.001.

[17] P.E. Campana, H. Li, J. Zhang, R. Zhang, J. Liu, J. Yan Economic, Optimization of photovoltaic water pumping systems for irrigation, Energy Convers. Manag. 95 (2015) 32–41, https://doi.org/10.1016/j.enconman.2015.01.066.

[18] D.H. Muhsen, A.B. Ghazali, T. Khatib, I.A. Abed, E.M. Natsheh, Sizing of a standalone photovoltaic water pumping system using a multi-objective evolutionary algorithm, Energy 109 (2016) 961–973, https://doi.org/10.1016/j.energy.2016.05.070.

[19] D.H. Muhsen, A.B. Ghazali, T. Khatib, Multiobjective differential evolution algorithm-based sizing of a standalone photovoltaic water pumping system, Energy Convers. Manag. 118 (2016) 32–43, https://doi.org/10.1016/j.enconman.2016.03.074.

[20] S. Abdourraziq, M.A. Abdourraziq, C. Darab, Photovoltaic water pumping system application in Morocco, in: 2017 11th Int. Conf. Electromechanical Power Syst. SIELMEN 2017 - Proc, 2017-Janua, 2017, pp. 271–274, https://doi.org/10.1109/SIELMEN.2017.8123331.

[21] M. Shirinabadi, A. Azami, The feasibility of photovoltaic and grid-hybrid power plant for water pumping station in tabriz-Iran, in: PVCon 2018 - Int. Conf. Photovolt. Sci. Technol., 2018, pp. 3–6, https://doi.org/10.1109/PVCon.2018.8523971.

[22] H. Singh, B.K. Saxena, K.V.S. Rao, Performance study of a solar photovoltaic water pump used for irrigation at Jaipur in Rajasthan, India, in: Proc. 2017 IEEE Int. Conf. Technol. Adv. Power Energy Explor. Energy Solut. An Intell. Power Grid, TAP Energy 2017, 2018, pp. 1–6, https://doi.org/10.1109/TAPENERGY.2017.8397225.

[23] I.B. Carrêlo, R.H. Almeida, L. Narvarte, F. Martinez-Moreno, L.M. Carrasco, Comparative analysis of the economic feasibility of five large-power photovoltaic irrigation systems in the Mediterranean region, Renew. Energy 145 (2020) 2671–2682, https://doi.org/10.1016/j.renene.2019.08.030.

[24] M.T.A.I. Khan, S. Sarkar, S. Hossain, A.U. Ahmed, B.B. Pathik, The feasibility study of solar irrigation: economical comparison between diesel and photovoltaic water pumping systems for different crops, in: 2013 Int. Conf. Electr. Inf. Commun. Technol. EICT 2013, 2014, https://doi.org/10.1109/EICT.2014.6777844.

[25] M.R. Haider, A. Shufian, M.N. Alam, M.I. Hossain, R. Islam, M.A. Azim, Design and implementation of three-Axis solar tracking system with high efficiency, in: 2021 *Int. Conf. Inf. Commun. Technol. Sustain. Dev. ICICT4SD 2021 - Proc*, 2021, pp. 1–5, https://doi.org/10.1109/ICICT4SD50815.2021.9396779.

[26] EU Energy prices. https://energy.ec.europa.eu/topics/markets-and-consumers/eu-energy-prices_en (accessed Jan. 05, 2022).

[27] World Bank Group, Commodity Markets Outlook, October 2021, p. 2021.

[28] International Energy Agency, World energy outlook 2021 [Online]. Available: www.iea.org/weo, 2021. (Accessed 5 January 2022).

[29] X. Zhuan, X. Xia, Optimal operation scheduling of a pumping station with multiple pumps, Appl. Energy 104 (2013) 250–257, https://doi.org/10.1016/j.apenergy.2012.10.028.

[30] J. Reca, A. García-Manzano, J. Martínez, Optimal pumping scheduling model considering reservoir evaporation, Agric. Water Manag. 148 (2015) 250–257, https://doi.org/10.1016/j.agwat.2014.10.008.

[31] I. Fernández García, M.A. Moreno, J.A. Rodríguez Díaz, Optimum pumping station management for irrigation networks sectoring: case of Bembezar MI (Spain), Agric. Water Manag. 144 (2014) 150–158, https://doi.org/10.1016/j.agwat.2014.06.006.

[32] I.J. Karassik, J.P. Messina, P. Cooper, C.C. Heald, Pump Handbook, McGRAW-HIL., New York, NY, USA, 2001.

[33] I. Sârbu, I. Borza, Energetic optimization of water pumping in distribution systems, Period. Polytech. ser. mech. eng. 42 (4) (1998) 141–152.

[34] FAOSTAT-Irrigation data in different countries. https://www.fao.org/faostat/en/#data/RL (accessed Apr. 01, 2022).

[35] Global Solar Atlas. https://globalsolaratlas.info/map?c=41.885597,-0.39196,11&s=41.885597,-0.39196&m=site (accessed Mar. 30, 2022).

[36] D.L. Talavera, E. Muñoz-Cerón, J.P. Ferrer-Rodríguez, P.J. Pérez-Higueras, Assessment of cost-competitiveness and profitability of fixed and tracking photovoltaic systems: the case of five specific sites, *Renew. Energy*. Apr. 134 (2019) 902–913, https://doi.org/10.1016/j.renene.2018.11.091.

[37] W. Nsengiyumva, S.G. Chen, L. Hu, X. Chen, Recent advancements and challenges in solar tracking systems (sts): a review, Renew. Sustain. Energy Rev. 81 (February 2017) (2018) 250–279, https://doi.org/10.1016/j.rser.2017.06.085.