Journal of Cleaner Production 316 (2021) 128386

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Optimal short-term water-energy dispatch for pumping stations with grid-connected photovoltaic self-generation

Natalia Naval, Jose M. Yusta *

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

ARTICLE INFO

Handling editor: Kathleen Aviso

Keywords:
Renewable energy
Pumping system
Optimal dispatch
Water-energy nexus
Self-consumption
Power converters

ABSTRACT

Increases in the energy costs of irrigation water pumping facilities puts the economic sustainability of recent investments in the modernization of farms at risk. To address this problem, it is essential to apply renewable technologies for the production of electricity, and photovoltaic energy is particularly attractive due to its lower cost and recent technological advances. The aim of this research is to develop a mathematical techno-economic dispatch model that optimizes the hourly schedule of pumping equipment subject to electrical and hydraulic constraints to minimize the weekly operating costs of a real pumping station. The resulting model is formulated as a mixed-integer nonlinear programming problem that determines the optimal hourly combination of pumping equipment and available resources to meet water and energy needs. The proposed model comprises fixed and variable speed pumps, a grid-connected photovoltaic plant, and two water ponds for internal regulation and storage. The results verify that the combination of self-consumption photovoltaic facilities and variable speed drives make it possible to maximize the percentage of self-consumed energy up to 99.41% during the month with the highest demand for water. In this case, the pumping station reduces its energy costs by 21.56%, in addition to improving water management.

1. Introduction

Irrigation water pumping facilities consume large amounts of electricity in addition to representing complex water management systems. Generally, energy consumption represents more than 90% of the total costs, while the initial investment cost of pumping equipment rarely represents more than 5% of the total costs during its life cycle (Karassik et al., 2001; Yates and Weybourne, 2001). The other 5% corresponds to maintenance of the equipment.

In recent years, irrigation facilities have focused on modernization. To this end, different solutions have been implemented to expand the use of water resources through pressure irrigation systems (aspersion, drip) replacing traditional gravity irrigation systems. There have also been advances in elements associated with these systems that enable automated water regulation, such as reception ponds, storage ponds, variable speed drives, and starters. By modernizing irrigation systems, it is possible to considerably reduce losses due to evaporation and infiltration and thus to better manage resources; however, modernization also implies an increase in energy needs because greater pressure is required compared to traditional systems.

At the same time, all countries have encouraged the implementation of renewable generation facilities to address the effects of climate change and increases in energy pricing. Pumping stations not only seek to maximize the use of available water for irrigation but also to improve their energy efficiency. Thus, many irrigation communities have begun to invest in photovoltaic self-consumption plants for irrigation water pumping in order to exploit energy incentives. Renewable production facilities can help maintain the economic sustainability of the heavy investments made by farmers to modernize their farms and allow still-pending projects to be completed. In global economic terms, the expansion of self-consumption allows for greater presence of renewables in the electricity market, with a foreseeable reduction in wholesale energy prices. In technical terms, self-consumption reduces losses in electrical grids by producing part of the electricity in the same place it is consumed. The application of these renewable technologies for electricity production must consider the coupling of electricity production with the electricity demand of the pumping stations as well as the technical limitations of pumping and storage hydraulic facilities.

Focusing on the design of pumping stations Guyer (2012) provides guidelines for determining the appropriate sizing of system components such as pumps, variable frequency drives, flow meters, pipes, and valves.

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

https://doi.org/10.1016/j.jclepro.2021.128386
Received 6 February 2021; Received in revised form 23 June 2021; Accepted 17 July 2021
Available online 18 July 2021

Nomenclature

Indexes

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

Data

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

Variables

P^h_{exp}	hourly energy exported to the grid (kWh)
P^h_{imp}	hourly energy imported from the grid (kWh)
I^h_{exp}	binary variable equal to 1 if energy is exported from the pumping station; otherwise, it is equal to 0
I^h_{imp}	binary variable equal to 1 if energy is imported to the pumping station; otherwise, it is equal to 0
$I^h_{FP_i}$	binary variable equal to 1 if the fixed-speed pump i is running; otherwise, it is equal to 0
$I^h_{VP_j}$	binary variable equal to 1 if the variable-speed pump j is running; otherwise, it is equal to 0
$Q^h_{FP_i}$	hourly flow rate of fixed-speed pump i $\left(\frac{m^3}{h}\right)$
$Q^h_{VP_j}$	hourly flow rate of variable-speed pump j $\left(\frac{m^3}{h}\right)$
$V^h_{pond_{st}}$	hourly volume of the storage pond (m^3)
$V^h_{pond_{rec}}$	hourly volume of the 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)
$I^h_{start_i}$	binary variable equal to 1 if pump i begins to function; otherwise, it is equal to 0
$C^h_{start_i}$	hourly start-up cost of pump i (€)
C^h_{start,r_i}	actual hourly start-up cost of pump i (€)

Another contribution on the design phase (Pulido-Calvo and Gutiérrez-Estrada, 2006) centers the research on the annual depreciation costs of pumps and reservoirs and the operation schedule in an optimization model.

In relation to energy efficiency, Tarjuelo et al. (2015) review the technical aspects of the modernization process of pumping stations. They analyze the management of irrigation systems and conclude that water efficiency improves but energy demand and investment costs increase. Brati et al. (2018) evaluate different solutions for improving the energy efficiency of pressurized irrigation systems, verifying that the factors that most influence system efficiency are the types of pump and electric motor, operating conditions, and dimensions of special elements such as valves, hydrants, and pipes. Sharu and Ab Razak (2020) focus on the different parameters that affect hydraulic performance in drip irrigation systems, such as the coefficient of uniformity or variation.

Most of the reviewed studies aim to minimize pump operating costs and use different mathematical methods, particularly integer programming (Galindo et al., 2017; Reca et al., 2015; Zhuan and Xia, 2013) or heuristic methods based on genetic algorithms (Alonso Campos et al., 2020; De Ocampo and Dadios, 2017; Rasoulzadeh-Gharibdousti et al., 2011). In (Galindo et al., 2017), the model consists of two stages: first, water distribution is scheduled by minimizing electricity prices, and second, the pumps are scheduled for maximum efficiency. Zhuan and Xia (2013) propose a dynamic scheduling model for the optimal operation configuration of a pumping station with several pumps. In (Reca et al., 2015), mathematical model also includes evaporation water losses. Additionally, Rasoulzadeh-Gharibdousti et al. (2011) include the annualized investment cost of a water pumping system in Iran. The approach used to combine nonlinear programming and heuristic methods provides rapid convergence and ease of use to obtain optimal solutions to complex problems. De Ocampo and Dadios (2017) study the influence of several optimization parameters in genetic algorithm (population size and mutation function) to obtain the most optimal solution for operating cost minimization. Alonso Campos et al. (2020) include the surplus power penalty in operating costs while minimizing the pressure required for each hydrant. Tricarico et al. (2014) propose a methodology for a multi-objective model for water distribution systems that seeks to optimize the operating costs of the pumps, the pressure necessary, and the income derived from pumps operating as turbines for energy recovery.

Regarding the incorporation of photovoltaic facilities in irrigation systems, Li et al. (2017) present a comprehensive review focusing on components, parameters that affect performance, optimization methods, and applications. Almeida et al. (2018) establish a method for selecting solar pumps that operate at a variable frequency. Narvarte et al. (2019) present a methodology that defines the number of solar panels required for large irrigation systems to avoid losses in photovoltaic energy production, such as motor voltage, grid voltage, or temperature. Campana et al. (2015) include the investment costs of a photovoltaic plant in their optimization model.

Regarding the management of irrigation water, the storage pond is an important component, and some research focuses on its optimization to minimize the operating costs of pumping facilities. For instance, Al-Ani and Habibi (2013) aim to optimize the operation of a pumping station and reservoir capacity through a heuristic method. Furthermore, Kim et al. (2006) highlight that the strategy of pumping water to a storage reservoir results in more continuous pumping, higher efficiency, and lower energy costs. However, the reservoir must be close to the pumping station to ensure minimal friction losses in the pipes and to avoid increasing energy requirements and thus total costs.

Other studies analyze effective water management from economic and environmental viewpoints through the study of sectorization in irrigation network design and the incorporation of pumps with variable speed drives (Fernández García et al., 2014). Results show significant energy savings while also guaranteeing service pressure in the hydrants. Soonthornnapha (2017) studies the optimal scheduling of several variable-speed pumps in a water distribution system in Thailand. Córcoles et al. (2016) propose a methodology for calculating optimal pressure and thus minimizing the energy consumed by the pumping station. They demonstrate that the installation of variable pressure regulation elements in the pumping system improves the system's energy efficiency. Recently, Cimorelli et al. (2020) analyze the application of two pump scheduling strategies in water distribution systems based on fixed-speed pumps and variable speed drives from technical and economic perspectives. Occasionally, the economic savings of using variable speed drives do not compensate for the start-up costs of the drives, especially in low-power pumping stations. However, from an environmental perspective, it is possible to significantly increase energy savings and reduce carbon dioxide emissions.

Lima et al. (2018) and Lima et al. (2019) propose a tool that simulates an irrigation network to minimize energy costs and considers the distribution of the crops as well as their water requirements. Additionally, different irrigation strategies are studied.

Based on the literature reviewed, the proposed models are overly simplistic since they do not include self-consumption photovoltaic generation facilities or the joint management of water demand and electricity consumption. In addition, these models do not take into account the filling and emptying strategies of the reception and storage ponds or the other hydraulic and electrical constraints applied to a real irrigation water pumping system. To overcome these gaps, this study focuses on addressing the challenge of joint management of water and energy consumption in water pumping facilities. The goal of this paper is the development of a new mathematical model for optimal hourly scheduling of the pumps in a real water pumping system with photovoltaic self-consumption. The proposed model is a mixed-integer nonlinear programming model that aims to minimize operating costs for a week depending on solar availability, the water levels of the ponds, and the hourly cost of the electricity required to meet water demand.

The main contributions of this article are summarized as follows:

- The development of a new optimal techno-economic dispatch model that obtains the optimal pumping schedule to satisfy irrigation needs at a minimum cost.
- The integration of different types of pumps (fixed and variable speed), a grid-connected photovoltaic self-consumption plant, and two water ponds (reception and storage) in the proposed model.
- The application of this model to the operation of a real pumping station.

The article is structured as follows: Section 2 explains the mathematical techno-economic dispatch model. Section 3 describes the real case study and analyzes the results obtained from the application of the model. Section 4 presents different case studies varying the demand in the model. Finally, Section 5 presents the main conclusions of this study.

2. Mathematical model

Irrigation communities use different strategies for pumping and storing water. Some allow direct pumping for irrigation and simultaneous pumping to a storage pond for further use of water; others do not have a storage pond and therefore have a more limited capacity to manage water resources or are subject to hydraulic limitations against using all the pumping power. In pumping stations, it is common to incorporate pumps with a variable speed drive, which allows precise regulation of the flow rates supplied by the pump according to needs at each instant. As a result, its operation is fully optimized, thereby achieving great energy savings. As discussed in Section 1, due to current energy incentives in many countries, irrigation communities are beginning to invest in the implementation of grid-connected photovoltaic facilities that help to achieve the economic, energy, and environmental balance of pumping stations. Generally, if a pumping station is unable to meet irrigation demand by its own photovoltaic production plant, energy can be acquired from the grid at a fixed price determined by the tariff period. When surpluses of photovoltaic generation occur, energy can be exported to the grid in exchange for remuneration.

Thus, the need to integrate energy and water management in irrigation pumping facilities to improve efficiency, reduce operating costs, and improve farms' economic viability is evident. This research therefore aims to develop a short-term techno-economic dispatch model to obtain the optimal irrigation water pumping schedule over 1 week at minimum operating costs of a pumping station with photovoltaic self-consumption. The proposed model must meet the facility's water irrigation demand as well as its electrical and hydraulic constraints (see Fig. 1). For this reason, the system purchases energy from the grid if the photovoltaic generation is not enough to meet demand. Otherwise, if power surpluses are produced, these are injected into the distribution network. It is worth mentioning that hourly water demand and photovoltaic generation forecasts are available for the dispatch model, in addition to prices for selling surplus energy to the day-ahead electricity market (OMIE, 2020).

The variables are defined every hour for a week for the proposed model and are classified according to their type as follows:

Binary variables (0,1) for decision-making in this model:

- import from or export energy to the grid in the pumping station (I^h_{imp}, I^h_{exp})
- operating status for each fixed or variable pump of the system ($I^h_{FP_i}$, $I^h_{VP_j}$)
- start-up of the fixed-speed pumps ($I^h_{start_i}$)

Integer variables:

- power of the fixed-speed pumps ($P^h_{FP_i}$)

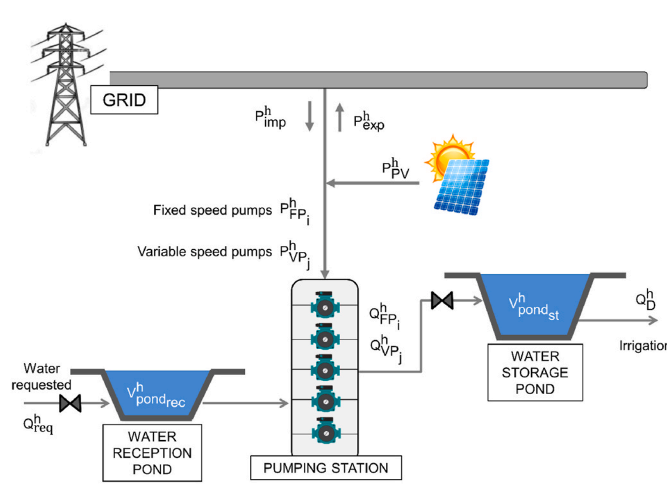

Fig. 1. Diagram of the techno-economic dispatch model.

- flow rate of the fixed-speed pumps ($Q^h_{FP_i}$)

Continuous variables:

- power of the variable-speed pumps ($P^h_{VP_j}$)
- flow rate of the variable-speed pumps ($Q^h_{VP_j}$)
- amount of energy imported from or exported to the grid in the pumping station (P^h_{imp}, P^h_{exp}).
- volume of water in the reception and storage ponds ($V^h_{pond_{rec}}$, $V^h_{pond_{st}}$)

2.1. Objective function

Once the variables of the problem are defined, Equation (1) presents the objective function to be optimized, which includes both the operating costs of the pumping equipment and the income derived from the sale of surplus photovoltaic production ($\rho^h_{exp} \cdot P^h_{exp}$). The sale price is only subject to the hourly price established by the wholesale electricity market. Regarding the costs of the system, in addition to the costs of purchasing energy from the grid ($\rho^h_{imp} \cdot P^h_{imp}$), start-up costs of fixed-speed pumps are considered (C^h_{start,r_i}). The continuous starting and stopping of the pumps is very inefficient because it can lead to instabilities in the hydraulic system and wear out the electric motors and pumps.

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

2.2. Constraints

The hydraulic and electrical constraints of the optimization model are described below.

Equation (2) shows the energy balance in the pumping system to meet hourly energy needs. As energy inputs into the pumping system, photovoltaic generation and energy imported from the grid are considered. Conversely, the energy consumed from the pumps and the energy exported to the grid are considered system outputs. Equations (3) and (4) establish the lower and upper limits of imported (P^h_{imp}) or exported (P^h_{exp}) energy of the pumping station during each hour. The upper limits are conditioned by the value of the integer decision variables (I^h_{imp}, I^h_{exp}). If photovoltaic generation (P^h_{PV}) is greater than the demand of the system, this implies that $I^h_{exp} = 1$ and $I^h_{imp} = 0$, so the system will export the excess production to the distribution network. In the opposite case where photovoltaic production is lower, $I^h_{exp} = 0$ and $I^h_{imp} = 1$, so the system will purchase energy from the grid to meet the required demand. In addition, the system can also neither import nor export energy, so the integer decision variables, I^h_{imp}, I^h_{exp}, will be equal to 0. Equation (5) imposes that the energy imported from the grid each hour cannot exceed the contracted power (P^h_c) in each tariff period to avoid economic penalties for surplus power. Equation (6) requires the maximum hourly amount of energy exported to the grid to be determined by available photovoltaic generation. It is worth mentioning that the hourly operations of importing from and exporting energy to the grid cannot occur simultaneously, so the sum of the binary variables (I^h_{imp}, I^h_{exp}) must be less than or equal to 1, as stated in Equation (7).

Regarding pump power, Equation (8) defines the behavior of fixed-speed pumps ($P^h_{FP_i}$). These pumps are characterized by an all-or-nothing operating mode, that is, when a pump of this type is operating, the power corresponds to its rated power, but otherwise its value is zero. Equation (9) expresses the power of the variable-speed pumps. The application of the affinity laws of pumps relates flow and power to rotational speed (Soonthornnapha, 2017). Flow rate decreases proportionally when the rotational speed of the pump shaft decreases, while absorbed power is proportional to the cube of the rotational speed. According to these relationships, an equation is obtained that links the absorbed power ($P^h_{VP_j}$) and flow rate ($Q^h_{VP_j}$) of the pump for any pump speed. In Equation (10), the constant k_{VP} is defined, which represents the known pump operating point at nominal frequency (f_{nom}).

For the characterization of the pumping equipment, it is assumed that the hydraulic head does not change because the losses due to friction and accessories of the system are so small they can be neglected. Pipes are usually sized with sufficiently large diameters to achieve efficient water transport and distribution systems (Perpiñan Lamigueiro, 2012). Moreover, ponds are built with large surfaces to maintain the height of the water sheet without great variations. On the other hand, according to Sârbu and Borza (1998), variations in performance when modifying the rotational speed of the pump can be mostly neglected for large pumps if the speed variation does not exceed 33% of the pump's nominal speed; therefore, this model considers this approximation.

Equations (11) and (12) establish the activation sequence of the fixed-speed and variable-speed pumps of the system, respectively, as it may be necessary to work with more or fewer pumps according to water demand. The binary variables $I^h_{FP_i}$ *and* $I^h_{VP_j}$ determine if the fixed-speed and variable-speed pumps run every hour.

Equation (13) shows the calculation of the corresponding water level for each hour of the reception pond ($V^h_{pond_{rec}}$). Q^h_{req} is the requested hourly flow rate to reach the reception pond of the pumping station from the water transport channels of the system. Equation (14) expresses the hourly water level of the storage pond ($V^h_{pond_{st}}$). Q^h_D represents the hourly flow rate of irrigation demand. Equation (15) expresses the total hourly flow pumped by the pumping system ($Q^h_{pump,total}$). Equations (16) and (17) indicate the upper and lower capacity limits of the reception pond and storage pond, respectively. The level of the ponds should be the same at the beginning and end of the study period (Equation (18)). The upper and lower limits of the water flows capable of passing through fixed and variable pumps of the system are defined in Equations (19) and (20), respectively.

Finally, Equations (21) and (22) determine the start-up costs of fixed-speed pumps since discontinuous operation of the pumps should be avoided. A variable (C^h_{start,r_i}) is defined that considers the costs of starting a pump, and a binary variable ($I^h_{start_i}$) is defined to make this decision. This binary variable takes a value equal to 1 if a pump starts working and otherwise remains 0. Equation (23) indicates that the start-up cost ($C^h_{start_i}$) is bound at the upper limit by means of a positive dimension (M) and at its lower limit by a negative dimension (m). k_{start} is a constant corresponding to the start-up cost of a pump.

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

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

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

$$P^h_{imp_{max}} = P^h_c \tag{5}$$

$$P^h_{exp_{max}} = P^h_{PV} \tag{6}$$

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

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

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

$$k_{VP} = \frac{P_{VP_j}\left(f_{nom}\right)}{Q^3_{VP_j}\left(f_{nom}\right)} \quad (10)$$

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

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

$$V^h_{pond_{rec}} = V^{h-1}_{pond_{rec}} + Q^h_{req} - Q^h_{pump,total} \quad (13)$$

$$V^h_{pond_{st}} = V^{h-1}_{pond_{st}} - Q^h_D + Q^h_{pump,total} \quad (14)$$

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

$$V^h_{pond_{rec,min}} \leq V^h_{pond_{rec}} \leq V^h_{pond_{rec,max}} \quad (16)$$

$$V^h_{pond_{st,min}} \leq V^h_{pond_{st}} \leq V^h_{pond_{st,max}} \quad (17)$$

$$V^h_{pond_{st}}\left(0\right) = V^h_{pond_{st}}\left(N_h\right) \quad (18)$$

$$Q^h_{FP_i} = Q^h_{FP_i,rated} \cdot I^h_{FP_i} \quad (19)$$

$$Q^h_{VP_j,min} \cdot I^h_{VP_j} \leq Q^h_{VP_j} \leq Q^h_{VP_j,max} \cdot I^h_{VP_j} \quad (20)$$

$$C^h_{start,r_i} = C^h_{start_i} \cdot I^h_{start_i} \quad (21)$$

$$C^h_{start_i} = k_{start} \cdot \left(I^h_{FP_i} - I^{h-1}_{FP_i}\right) \quad (22)$$

$$m \cdot \left(1 - I^h_{start_i}\right) \leq C^h_{start_i} \leq M \cdot I^h_{start_i} \quad (23)$$

The mathematical optimization problem is a mixed-integer nonlinear programming type (MINLP) problem, which proposes the best possible combination of pumping equipment and available resources every hour to meet water and energy needs for a week. In recent years, new methods and software for resolving complex problems on small and large scales have been developed. This study used GAMS®, a powerful software program that allows the modeling, analysis, and optimization of various types of mathematical models with a large number of equations and variables (linear, nonlinear, or mixed-integer), in addition to providing a wide variety of solvers (Corporation, 2013). Bonami et al. (2008) and Kronqvist et al. (2019) compare different optimization algorithms; this study used BONMIN-HYB due to its robustness and high efficiency. This method is based on a hybrid external approach that uses branching and cutting techniques for the resolution of the proposed mixed-integer nonlinear model with a runtime of 5 h 35 min using a computer with an Intel® Core i7 processor, 3.00 GHz CPU, and 16 GB of RAM. The optimization process followed by the aforementioned solver consists of solving the relaxation of nonlinear subproblems in additional nodes of the tree as well as performing local searches in the nodes, which guarantees an optimal solution to the problem (Bonami et al., 2008).

3. Case study

3.1. Baseline data

The pumping station analyzed in this article is located in the province of Huesca (Spain) and irrigates an area of approximately 2800 ha, for which it has five parallel pumps that all work to deliver water from the reception pond to the storage pond (see Fig. 1). Four of the five pumps are fixed-speed pumps of 400 kW rated power. The fifth is a 400 kW pump equipped with a variable-speed drive to efficiently adapt the flow to the required demand. In addition, the pumping station has a 1.5 MW photovoltaic plant to reduce energy costs and the environmental impact of the agricultural sector. Pumping systems often have a lifespan of 15–20 years, while photovoltaic panels can reach up to 25 years.

The main components of the analyzed pumping station consist of the following (see Fig. 2):

- Photovoltaic modules (3334) that capture solar radiation and convert it into energy for the pumping system. The photovoltaic modules of the pumping station are fixed on the ground and therefore do not require much maintenance.
- Six DC-AC inverters that allow the photovoltaic energy produced to be injected into the pumping station or into the grid through the conversion of the direct current (DC) generated by the photovoltaic modules into alternating current (AC) for power line frequency.
- One variable frequency drive (VFD) that allows the pump to be started and stopped smoothly and adapts the flow to irrigation demand by modifying the rotation frequency of the electric motor.
- Four starters in fixed-speed pumps that allow control of the three phases of the asynchronous motor by regulating the voltage and current during starting and stopping, thus providing effective control of the torque.
- Five centrifugal pumps that transform mechanical energy into hydraulic energy and are responsible for driving water through the pipes. The characteristic curves of these pumps allow the flow to be related to the head generated and the power absorbed. The affinity laws determine the behavior of the pumps according to the speed of rotation. Each pump is driven by a three-phase asynchronous motor.

The control method of the variable frequency drive is based on voltage-frequency control. This strategy consists of maintaining a constant ratio between the supply voltage and frequency of the power supplied to the motor as the frequency is varied to regulate the motor's rotation speed. The VFD uses the pulse-width modulation (PWM) technique to construct a specific AC sine wave; this technique requires switching the inverter power devices (transistors or Insulated Gate Bipolar Transistors) on and off many times to generate the proper RMS voltage levels.

On the other hand, the control strategy of the inverter is based on the maximum power point tracking (MPPT) that enables the best performance of the solar panels as it seeks to exploit the maximum available power at all times.

The technical specifications of the motor-pump and variable frequency drive are indicated in Tables 1 and 2, respectively.

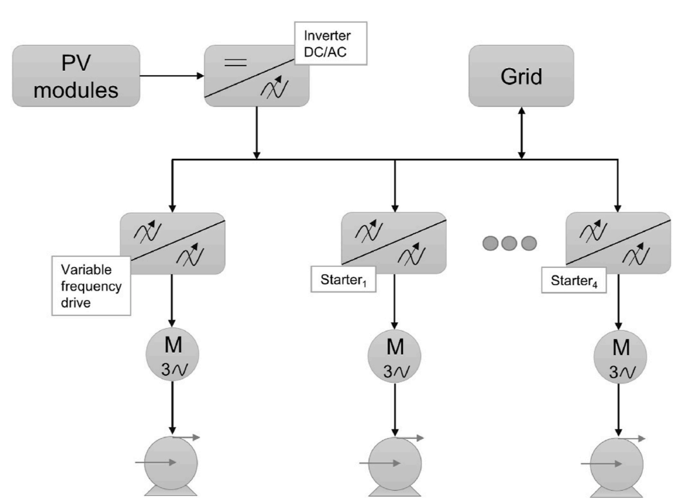

Fig. 2. Block diagram of the pumping station.

Table 1
Technical specifications of motor and pump (ABB, 2020).

Pump model	**STR 400/10/480**
Manufacturer	Sulzer
Rated flow (m^3/h)	1967
Head (m)	54.2
Motor type	ABB M3BP 355MLA 4
Power (kW)	400
Rated voltage (V)	690
Rated current (A)	409
Rated speed (rpm)	1489
Torque (Nm)	2565
Number of poles	4

Table 2
Technical specifications of variable frequency drive (Rockwell Automation, 2020).

Model	PowerFlex 755 AC Drive
Manufacturer	Rockwell Automation
Output current (A)	415
Voltage rating (V)	690
Power (kW)	450 Light Duty
	400 Normal Duty
	355 Heavy Duty

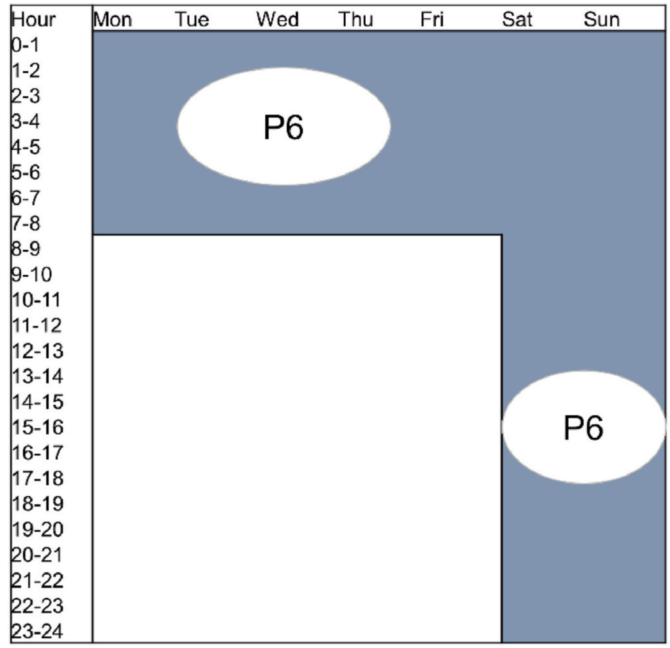

Fig. 4. Hourly distribution for period 6 of the electricity tariff.

Fig. 3 shows the seasonality of the electricity consumption of the pumping station in 2019, with the beginning and end of the irrigation season clearly seen through the higher consumption from May to September.

This irrigation community has contracted a high-voltage electricity tariff at a fixed-price for six periods. In other words, the energy retailer and the consumer reach an agreement on a single kWh price for each of the tariff periods throughout the year. The irrigation community studied concentrates its energy consumption in period 6, which is associated with the lowest energy costs, corresponding to night hours and weekend hours throughout the year (see Fig. 4). Therefore, this system plans the operation of the pumps to maximize their use during these hours. The rest of the hours are associated with different periods according to the month of the year and have higher energy costs. It should be noted that the installation of a self-consumption photovoltaic plant in the system increases the number of pumping hours in the remaining hours of the day. In addition, the months of maximum solar radiation coincide with the months of greatest irrigation demand (May to September), which supports that a large amount of the photovoltaic energy produced can be self-consumed.

Table 3 shows the distribution of annual electricity consumption according to the tariff period, providing details of electricity prices and the power contracted in each period. The power contracted in period 6 covers the system's needs, while energy use during the most expensive periods is avoided and minimum power is contracted for the auxiliary services of the pumping station.

Table 3
Electrical data of the pumping station.

Period	Electricity consumption (MWh)	Electricity Price (€/MWh)	Power contracted (kW)
1	8.088	116.5	50
2	10.184	107	50
3	4.063	94	50
4	7.488	87	50
5	11.041	73.5	50
6	2688.280	59.4	2000

Tables 4 and 5 show the technical data of the reception and storage ponds as well as the pumps of the studied system. In water pumping facilities, pumps rarely work below 35 Hz due to decreases in pressure in

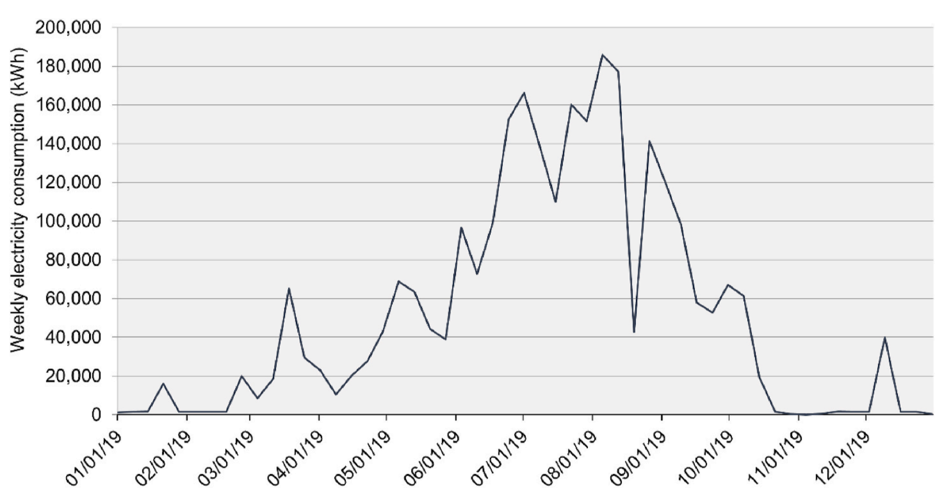

Fig. 3. Weekly electricity consumption in 2019.

Table 4
Technical data of the reception pond and storage pond of the pumping station.

Ponds	Minimum volume	Maximum volume
Reception pond (m^3)	75,000	155,000
Storage pond (m^3)	200,000	280,000

Table 5
Technical data of the pumping station pumps at different variable-speed drive frequencies.

Type	Number of pumps	Rated power 50 Hz (kW)	Rated flow 50 Hz (m^3/h)	Power 35 Hz (kW)	Flow rate 35 Hz (m^3/h)
Fixed-speed	4	400	1967	–	–
Variable-speed	1	400	1967	137.2	1377

the pump when speed is reduced. In addition, in this variation range, performance remains constant under changes in pump speed (Sârbu and Borza, 1998). In this situation, the pump only requires 1/3 of the initial power for the drive, demonstrating the great efficiency of using variable speed drives for flow regulation in these facilities.

Regarding the costs of the study pumping station, Table 6 indicates the initial cost of each of the main components of the system, and Table 7 includes the annual maintenance costs, which are highly variable depending on the year.

3.2. Results and discussion

The mixed-integer nonlinear hourly dispatch problem minimizes the operating costs of a pumping station with photovoltaic self-consumption through the optimal technical and economic management of water and energy to meet the required water demand. As a result, the optimal number of pumps of each type (fixed- and variable-speed) is determined, along with their respective values of power and flow, water levels of the reception and storage ponds, and the amount of imported electricity and electricity exported to the grid for each hour during the 168 h of a week.

To illustrate the operation of the proposed model, a week in July is analyzed, since it is the month with the highest demand for water and energy in the pumping station.

Fig. 5a represents the optimal hourly energy results to meet demand (see Fig. 5b) for one week. The greatest number of pumps in operation to meet the necessary water demand occurs at night or on weekends or at all hours during period 6 since these periods correspond to the lowest energy purchase price. It should be noted that the pumping strategy of this system during period 6 is to use energy acquired from the grid and to therefore maintain the minimum contracted power in the remaining tariff periods so as not to incur penalties for surpluses of power (see Table 3). At the end of the second day of the study week, the water storage pond reaches capacity, with a value of 276,667 m^3 (the maximum limit is 280,000 m^3). For the first few hours of the next day, water is only pumped with the variable-speed pump, with the fixed-speed pumps used only rarely and at specific times, leading to a peak in the pumped power of the system (hour 52; see Fig. 5b).

Table 6
Cost of each component of the pumping station.

Components	Unit	Unit price (€)	Total cost (€)
Photovoltaic modules 450 W	3334	90	300,060
Inverter	6	3250	19,500
Centrifugal pump and motor	5	36,250	181,250
Variable frequency drive	1	40,000	40,000
Starter	4	5000	20,000
Valves, filters, flow meters	–	–	1,200,000

Table 7
Annual maintenance costs of the pumping station.

Maintenance items	Annual cost (€)
Mechanical	
Bearings	3650
Electrical	
Labor and travel	3100
Motors	10,000
Transformers	2800
Annual inspection of the electrical installation	2350
Capacitor bank	2750
Other (electric equipment, automation)	3000

At the same time, the photovoltaic plant allows for more pumping hours by exploiting available solar energy as long as the upper and lower water levels of the ponds and the technical limits of the pumps are fulfilled. Thus, the system seeks to adapt at all times to the maximum production power of the photovoltaic plant. This system configuration reduces weekly costs by 21.56% compared to the system without a photovoltaic self-consumption plant. Fig. 6 depicts solar radiation within the study week. The first five days are clear-sky days with a clean sinusoidal curve, reaching a maximum production value at 12:00 a.m. However, the sixth day corresponds to a cloudy day with large fluctuations in irradiance, so less power is used. Finally, there are sparse clouds on the last day, resulting in some punctual irregularity in irradiance.

The irrigation system configuration of this pumping station with reception and storage ponds improves regulation so that it is possible to pump during low-cost hourly periods and to have on-demand irrigation in any hour period, including on cloudy days with low solar production. Fig. 7 shows the evolution of the optimal water levels of the ponds during a week of July. These levels simultaneously guarantee pumped water reaching the reception pond as well as the supply of water for agricultural irrigation from the storage pond.

Table 8 presents the hourly results for one day to allow detailed analysis of the optimal water and energy management of the pumping station. Based on the results, the use of a variable speed drive is essential for pumping water through solar panels because it varies the speed of the pump according to the power available in the photovoltaic generator. In this way, the maximum use of solar radiation for water pumping is achieved. The higher the irradiance is, the higher the output frequency and therefore the higher the pump speed, which translates into a higher pumping flow. The variable speed drive acts as if pumps of many powers were activated according to the needs required in each moment. Regarding fixed-speed pumps, they are activated according to system demand and are grouped to prevent the pumps from starting and stopping constantly, which would reduce the lifespan of the pumps and consume more electricity. Energy from the grid is purchased at night when energy costs are lowest to meet the irrigation demand and satisfy the constraints of the maximum imported power model of the network according to the contracted power in each hourly period, maintaining the water levels of the ponds within the capacity limits.

Fig. 8 depicts the results of the variable pump speed and flow rate for the day analyzed in Table 8. Pump flow is proportional to pump speed, according to the affinity laws. As noted, fixed-speed pumps operate on an all-or-nothing basis, so they always run at nominal speed, in this case 1489 rpm, providing their rated flow of 1967 m^3/h. Regarding the hydraulic head, it is assumed that this remains constant because friction losses are neglected and the surface of the water ponds is so large that the height of the water sheet is constant, as explained in Section 2. Hence, the hydraulic head is approximately 54.2 m.

Water is supplied to the pumping station from the water transport channels of the system between 0 and 8 h. Irrigation of agricultural fields also occurs at night for agronomic reasons; that is, between 0 and 8 h, water is moved from the storage pond to meet the irrigation demand. Consequently, although water is pumped from the reception pond

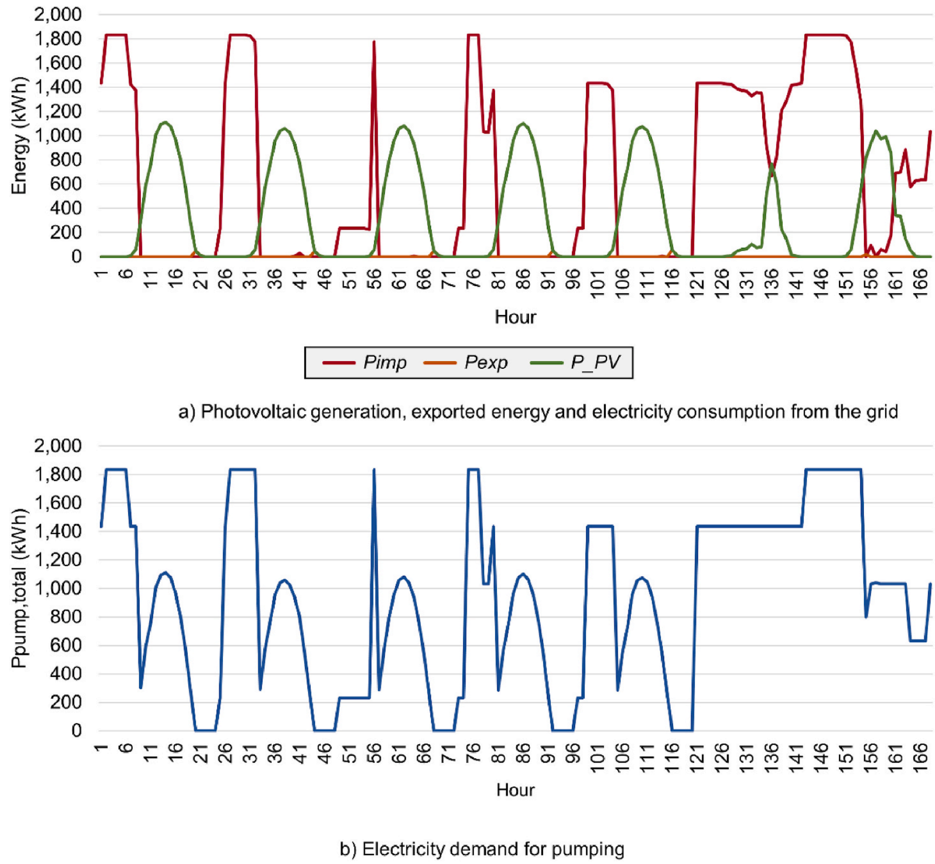

Fig. 5. Results of optimal hourly energy in July (07/15/2019–07/21/2019).

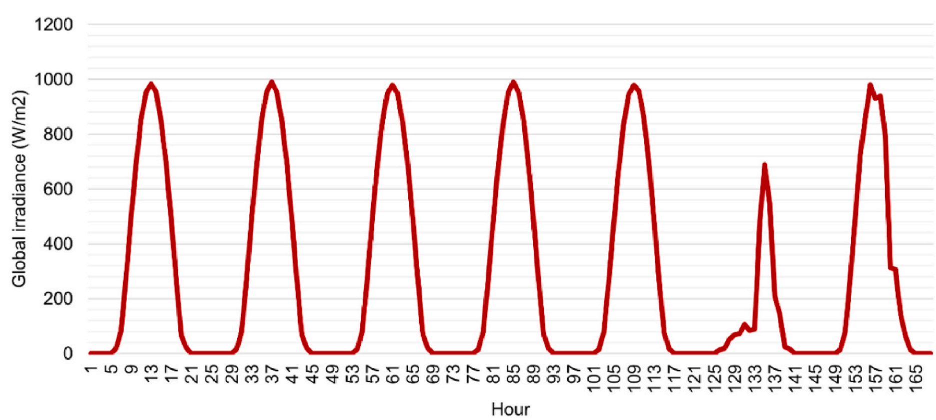

Fig. 6. Solar radiation during the study week.

to the storage pond in this hourly period, the reception pond is filled while the storage pond is emptied until both ponds are close to the maximum and minimum capacities, respectively. However, during the daytime, the water pumped using photovoltaic solar energy is stored in the storage pond for further use in irrigation.

Within this case study, the system can self-consume practically all the photovoltaic energy produced (99.41%) and increase the number of hours of water pumping in the different tariff periods. Only in the hours of very low solar radiation, when photovoltaic production is less than the minimum power capable of absorbing the variable-speed pump, does the system choose to sell that energy to the grid in exchange for remuneration.

In economic terms, for each kWh self-consumed, the pumping station saves the variable cost of electricity needed to pump the water to the storage pond, which is much higher than the income it can receive for each kWh of surplus energy because it only receives the price of energy in the wholesale market.

In conclusion, it is more economically profitable to self-consume as much as possible and to avoid exporting energy to the grid, even if income can be gained from the sale of electricity.

4. Analysis of scenarios

To illustrate the behavior of the model, three typical weeks during the irrigation season with different meteorological conditions and water demand are studied. In general, most crops increase their water requirements as solar irradiance increases, so there is a strong correlation between water needs and the production of photovoltaic energy to pump

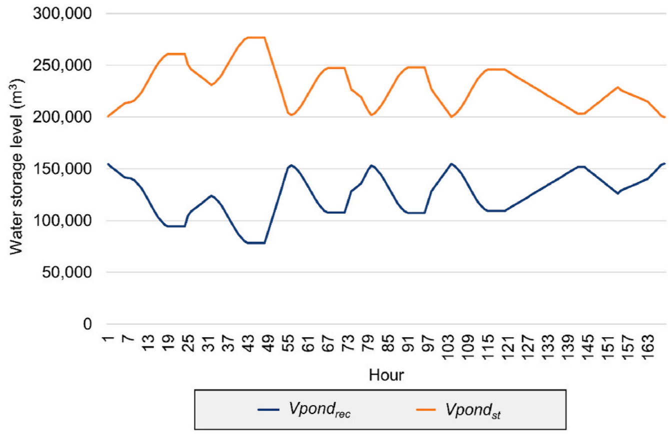

Fig. 7. Evolution of the optimal water levels of the ponds during one study week.

water.

Case 1. One week in April representative of the beginning of the irrigation season.

Case 2. One week in July during which there is the greatest demand for water. This case illustrates the operation of the model in Section 3.

Case 3. One week in September representative of the end of the irrigation season.

Table 9 compares the optimal weekly results obtained for each of the case studies. It shows that for all the case studies, the model trend is the same: to maximize the amount of self-consumed energy, by virtue of which the model decides the optimal scheduling of the pumping equipment and facilities, thereby minimizing the sale of surplus photovoltaic generation to the grid.

In Case 1, where the demand for irrigation is lower, using the hours of greatest solar radiation for pumping water is almost sufficient to meet water demand, so the amount of energy purchased from the grid is much lower compared to the rest of the cases. In addition, the amount of energy exported to the grid increases (3942 kWh), since there are several

Table 8
Optimal hourly results for a study day in July.

hour	P_{FP} (kW)	P_{VP} (kW)	$P_{pump,\ total}$ (kW)	Q_{FP} (m^3)	Q_{VP} (m^3)	$Q_{pump,\ total}$ (m^3)	Q_{req} (m^3)	Q_D (m^3)	$V_{pond_{rec}}$ (m^3)	$V_{pond_{st}}$ (m^3)	P_{PV} (kW)	P_{exp} (kW)	P_{imp} (kW)
1	–	234	234	–	1644	1644	12000	12000	117991	237009	–	–	233
2	–	234	234	–	1644	1644	12000	12000	128347	226653	–	–	233
3	1600	234	1834	7868	1644	9512	12000	12000	130835	224165	–	–	1833
4	1600	234	1834	7868	1644	9512	12000	12000	133323	221677	–	–	1833
5	1600	234	1834	7868	1644	9512	12000	12000	135811	219189	–	–	1833
6	800	234	1034	3934	1644	5578	12000	12000	142233	212767	–	–	1033
7	800	234	1034	3934	1644	5578	12000	12000	148655	206345	7	–	1027
8	1200	234	1434	5901	1644	7545	12000	12000	153110	201890	59	–	1375
9	–	286	286	–	1760	1760	–	–	151350	203650	286	–	–
10	400	167	567	1967	1470	3437	–	–	147913	207087	567	–	–
11	400	349	749	1967	1880	3847	–	–	144066	210934	749	–	–
12	800	167	967	3934	1471	5405	–	–	138661	216339	967	–	–
13	800	274	1074	3934	1735	5669	–	–	132992	222008	1074	–	–
14	800	302	1102	3934	1792	5726	–	–	127266	227734	1102	–	–
15	800	262	1062	3934	1709	5643	–	–	121623	233377	1062	–	–
16	800	158	958	3934	1443	5377	–	–	116246	238754	958	–	–
17	400	377	777	1967	1928	3895	–	–	112351	242649	777	–	–
18	400	148	548	1967	1413	3380	–	–	108971	246029	548	–	–
19	–	268	268	–	1720	1720	–	–	107251	247749	268	–	–
20	–	–	–	–	–	–	–	–	107251	247749	49	49	–
21	–	–	–	–	–	–	–	–	107251	247749	9	9	–
22	–	–	–	–	–	–	–	–	107251	247749	–	–	–
23	–	–	–	–	–	–	–	–	107251	247749	–	–	–
24	–	–	–	–	–	–	–	–	107251	247749	–	–	–

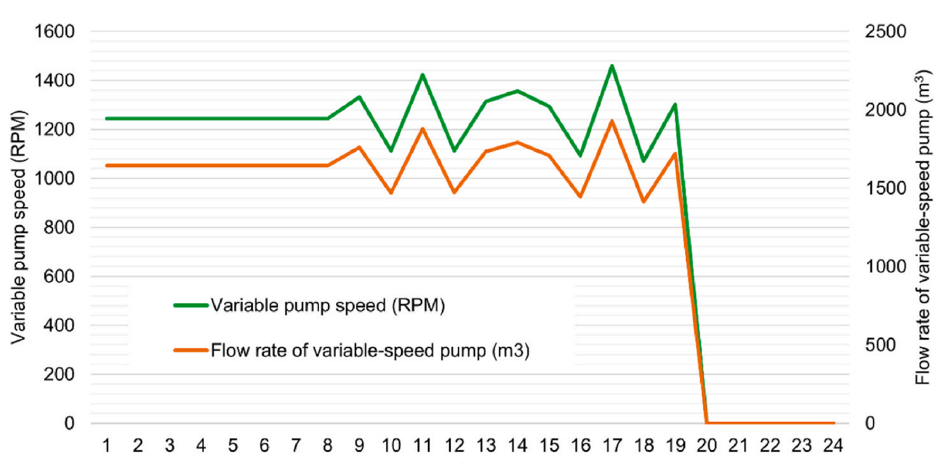

Fig. 8. Results of the variable pump speed and flow rate for a study day in July.

Table 9
Optimal weekly results of the three case studies.

Case	1	2	3
$Q_{pump,total}$ (m^3)	373,152	834,240	601,440
$P_{pump,total}$ (kWh)	58,580	156,004	107,304
P_{PV} (kWh)	45,402	52,404	46,322
P_{imp} (kWh)	17,120	103,909	61,562
P_{exp} (kWh)	3942	309	580
%self-consumption	91.32	99.41	98.75
kWh/m^3	0.1569	0.1870	0.1784
Total cost (€)	1033	6193	3670
Total income (€)	221	16	23
€/m^3	0.0028	0.0074	0.0061

hours when the solar radiation is less than the minimum power that the pump with a variable speed drive is able to absorb; as a result, these surpluses of energy are sold to the grid in exchange for remuneration. For this reason, the percentage of self-consumed energy with respect to the energy generated is 91.32%, which is slightly lower than the value obtained in the other case studies. On the other hand, in Cases 2 and 3, where the water demand is quite high, it is possible to self-consume nearly all the energy generated, 99.41% and 98.75%, respectively. However, in these cases, the pumping station needs to buy a greater amount of energy from the grid during the cheapest hours because it is not able to cover demand even with the maximum use of available photovoltaic production. As indicated in Table 9, the highest amount of self-consumed energy, 52,095 kWh, is achieved in Case 2. The maximum production of photovoltaic energy, 52,404 kWh, is almost reached, and thus the system almost entirely avoids exporting energy to the grid. However, the system still needs to buy a large amount of energy from the grid, 103,909 kWh, to satisfy the irrigation demand.

Table 9 also includes the ratio of energy consumed per volume of water, which is frequently used in the analysis of water pumping. The highest value obtained corresponds to Case 2 with a value of 0.1870 kWh/m^3, indicating that a greater number of fixed-speed pumps are operating, especially during night hours and weekends, to meet the irrigation demand in its entirety. In contrast, Case 1 presents the lowest ratio, 0.1569 kWh/m^3, because when a lower demand is required, the fixed-speed pumps rarely operate. In essence, the pump with a variable speed drive is the only pump operating during the week in Case 1 because it can adequately adjust the flow to the needs demanded by the system by modifying the rotational speed of the pump. In this case, it must operate for many hours in below-nominal flow conditions so that, by reducing the working frequency, energy consumption is also reduced, thereby fostering greater energy efficiency. This analysis is represented graphically in Fig. 9, which compares the number of hours the different pumps are operating for the case studies.

As illustrated in Fig. 9, in Case 1, the variable pump works 139 h during the week, while the fixed pumps work 83 h. Comparing the operating hours of the pumps in Cases 1 and 2, the fixed pumps work significantly fewer hours in Case 1 due to the lower pumping demand. However, the number of hours that the variable-speed pump works remains practically constant in Cases 1 to 3 because by regulating the flow rate supplied by the pump, there is an energy saving in the system, and the use of this pump is always more efficient.

5. Conclusion

The efficient use of energy and water constitutes a great challenge for irrigation from both the environmental and economic perspectives. To address this challenge, this study develops a mathematical model of hourly techno-economic dispatch to minimize the operating costs of several pumps with fixed and variable speeds over a week. In addition, the model integrates a self-consumption photovoltaic power plant and obtains optimal management of the pumping equipment and facilities that make up a real irrigation system.

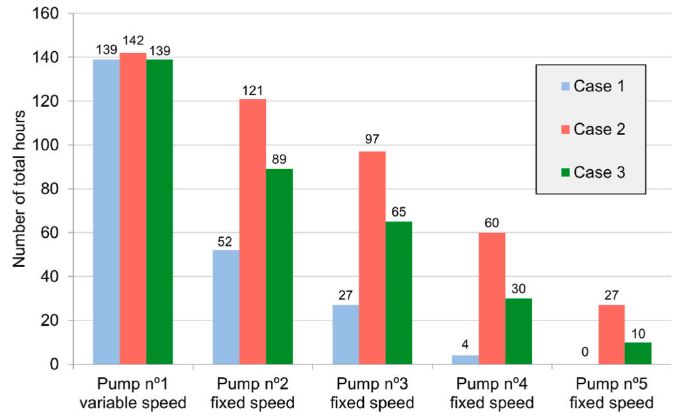

Fig. 9. Comparison of the number of pumping hours during one week for the three case studies.

The analysis of the results in different real cases verifies that the most economically profitable situation for the proposed model is to maximize self-consumption and minimize the surplus energy generated by the photovoltaic plant. In the case study of highest demand, 99.41% self-consumption is reached, but the water pumping system still has to purchase energy from the grid to meet the irrigation demand. In addition, the worst ratio of energy consumed per volume of water (0.1870 kWh/m^3) is obtained, since it is necessary that most of the fixed-speed pumps operate at night to satisfy water demand. During the daytime, the variable-speed pump continuously adjusts its power according to solar availability and irrigation needs to meet the irrigation demand and maintain the water levels of the ponds within their capacity limits. In contrast, in the case study of lowest demand, hardly any pumps work at night because a large part of the irrigation demand is satisfied with the use of solar production (91.32% self-consumption), and surpluses are sold to the grid. The best ratio of energy consumed per volume of water (0.1569 kWh/m^3) is obtained in this case because the variable-speed pump is practically the only pump operating, which increases the system's efficiency.

In short, the model proposed in this research offers a good strategy for efficiently managing water and energy consumption by using renewable energy to completely or partially meet demand in pumping facilities, and applying this model can contribute to improving the competitiveness and viability of agricultural operations.

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

ABB, 2020. https://new.abb.com/products/3GBP352410-ADG/m3bp-355mla-4. (Accessed 21 May 2021).

Al-Ani, D., Habibi, S., 2013. Optimal operation of water pumping stations. WIT Trans. Ecol. Environ. 178, 185–198. https://doi.org/10.2495/WS130161.

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

Alonso Campos, J.C., Jiménez-Bello, M.A., Martínez Alzamora, F., 2020. Real-time energy optimization of irrigation scheduling by parallel multi-objective genetic algorithms. Agric. Water Manag. 227, 105857. https://doi.org/10.1016/j.agwat.2019.105857.

Automation, Rockwell, 2020. URL. https://configurator.rockwellautomation.com/#/configurator/014D1A5F687C4EA08A7295631867639A/summary. (Accessed 21 May 2021).

Bonami, P., Biegler, L.T., Conn, A.R., Cornuéjols, G., Grossmann, I.E., Laird, C.D., Lee, J., Lodi, A., Margot, F., Sawaya, N., Wächter, A., 2008. An algorithmic framework for convex mixed integer nonlinear programs. Discrete Optim. 5, 186–204. https://doi.org/10.1016/j.disopt.2006.10.011.

Brati, H., Khaledian, M., Biglouei, M., Parvaresh Rizi, A., 2018. Assessment of energy efficiency in pump stations of pressurized irrigation systems (case study: qazvin and kermanshah provinces). Int. J. Agric. Manag. Dev. 8, 389–396.

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

Cimorelli, L., Covelli, C., Molino, B., Pianese, D., 2020. Optimal regulation of pumping station in water distribution networks using constant and variable speed pumps: a technical and economical comparison. Energies. https://doi.org/10.3390/en13102530.

Córcoles, J.I., Tarjuelo, J.M., Moreno, M.A., 2016. Methodology to improve pumping station management of on-demand irrigation networks. Biosyst. Eng. 144, 94–104. https://doi.org/10.1016/j.biosystemseng.2016.02.002.

Corporation, G.D., 2013. GAMS — the Solver Manuals. GAMS Dev. Corp.

De Ocampo, A.L.P., Dadios, E.P., 2017. Energy cost optimization in irrigation system of smart farm by using genetic algorithm. In: 2017IEEE 9th Int. Conf. Humanoid, Nanotechnology, Inf. Technol. Commun. Control. Environ. Manag. 1–7. https://doi.org/10.1109/HNICEM.2017.8269497.

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

Galindo, J., Torok, S., Salguero, F., de Campos, S., Romera, J., Puig, V., 2017. Optimal management of water and energy in irrigation systems: application to the bardenas canal. IFAC-PapersOnLine 50, 6613–6618. https://doi.org/10.1016/j.ifacol.2017.08.694.

Guyer, J.P., 2012. Introduction to pumping stations for water supply systems. Contin. Educ. Dev. 1–42.

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

Kim, J., Nason, J.A., Lawler, D.F., 2006. Regulating reservoirs in pressurized irrigation water supply systems. J. Water Supply Res. Technol. - Aqua 55, 461–470. https://doi.org/10.2166/aqua.2006.056.

Kronqvist, J., Bernal, D.E., Lundell, A., Grossmann, I.E., 2019. A review and comparison of solvers for convex MINLP. Optim. Eng. 20, 397–455. https://doi.org/10.1007/s11081-018-9411-8.

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

Lima, F.A., Martínez-Romero, A., Tarjuelo, J.M., Córcoles, J.I., 2018. Model for management of an on-demand irrigation network based on irrigation scheduling of crops to minimize energy use (Part I): model Development. Agric. Water Manag. 210, 49–58. https://doi.org/10.1016/j.agwat.2018.07.046.

Lima, F.A., Córcoles, J.I., Tarjuelo, J.M., Martínez-Romero, A., 2019. Model for management of an on-demand irrigation network based on irrigation scheduling of crops to minimize energy use (Part II): financial impact of regulated deficit irrigation. Agric. Water Manag. 215, 44–54. https://doi.org/10.1016/j.agwat.2019.01.006.

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

OMIE, 2020. URL. http://www.omie.es/inicio. (Accessed 29 December 2020).

Perpiñan Lamigueiro, O., 2012. Photovoltaic Energy 1–186.

Pulido-Calvo, I., Gutiérrez-Estrada, J.C., 2006. Selection and operation of pumping stations of water distribution systems. Environ. Res. J. 5, 1–20.

Rasoulzadeh-Gharibdousti, S., Haddad, O.B., Mariño, M.A., 2011. Optimal design and operation of pumping stations using NLP-GA. Proc. Inst. Civ. Eng. Water Manag. 164, 163–171. https://doi.org/10.1680/wama.1000044.

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

Sârbu, I., Borza, I., 1998. Energetic optimization of water pumping in distribution systems. Period. Polytech. ser. mech. eng. 42, 141–152.

Sharu, E.H., Ab Razak, M.S., 2020. Hydraulic performance and modelling of pressurized drip irrigation system. Water 12, 2295. https://doi.org/10.3390/w12082295.

Soonthornnapha, T., 2017. Optimal Scheduling of Variable Speed Pumps in Mahasawat Water Distribution Pumping Station. In: 2017 International Electrical Engineering Congress (IEECON). Pattaya,Thailand, pp. 1–4. https://doi.org/10.1109/IEECON.2017.8075752.

Tarjuelo, J.M., Rodriguez-Diaz, J.A., Abadía, R., Camacho, E., Rocamora, C., Moreno, M. A., 2015. Efficient water and energy use in irrigation modernization: lessons from Spanish case studies. Agric. Water Manag. 162, 67–77. https://doi.org/10.1016/j.agwat.2015.08.009.

Tricarico, C., Morley, M.S., Gargano, R., Kapelan, Z., De Marinis, G., Savić, D., Granata, F., 2014. Integrated optimal cost and pressure management for water distribution systems. Procedia Eng 70, 1659–1668. https://doi.org/10.1016/j.proeng.2014.02.183.

Yates, M.A., Weybourne, I., 2001. Improving the energy efficiency of pumping systems. J. Water Supply Res. Technol. 50, 101–111. https://doi.org/10.2166/aqua.2001.0010.

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