

Energy cost optimization in pressurized irrigation networks

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Abstract The increasing demand and price for energy are affecting all economic sectors, including irrigated agriculture. This sector has undergone substantial transformations to improve water use efficiency by adapting its open-channel distribution systems to pressurized networks, which entail greater energy consumption and hence higher energy costs. Farmers are therefore demanding measures to reduce energy costs and ensure the profitability of their farms. In this paper, previous energy optimization models focusing on network sectoring (WEBSOM) and critical points control (WECPM) are improved by incorporating an electricity tariff module that considers different energy prices according to the hour of the day and the day of the year. The model permits determining the minimum energy cost affected by different operation conditions of the network. The methodology has been analyzed in an irrigation network located in southern Spain in which different operation scenarios were evaluated: operation with and without sectors and with and without critical points control. The results show that adopting measures to improve the operation of critical points in months of peak energy demand and

operation by sectors in the others leads to a 13 % cost savings compared to the baseline scenario where only pressure heads at the pumping stations are optimized. The proposed model is a decision-making support system that integrates alternative irrigation network operation scenarios with the structure of the electricity tariff.

Introduction

Population growth and the associated rise in the demand for food entail greater pressures on the planet's resources. As a result, both energy and water consumption could increase by 40 % over the next twenty years. Irrigated agriculture, among other activities, plays an important role in securing food production. For this reason, the world area equipped for irrigation (287 M ha in 2005) is expected to increase by 32 M ha over the period 2005–2050 (Conforti 2011).

Agriculture is a sector with high water consumption. Water diverted for irrigation accounts for up to 90 % of the total water resources in arid developing countries (Brazilian et al. 2011). In Europe, irrigated agriculture uses around 33 % of total water used although this figure may reach over 80 % in countries of Southern Europe (EEA 2012). Spain has one-third of the irrigated area in Europe, and 73 % of its national freshwater is devoted to the irrigation sector (Instituto Nacional de Estadística (INE) 2014; MAGRAMA 2013). Nonetheless, the availability of water resources for irrigation is limited in most of the country's regions.

Due to the shortage of irrigation water, the two National Irrigation Modernization Plans established that irrigated areas switch from open-channel systems to pressurized water distribution networks (MAPA 2001; MMA 2006). Because this modernization process has enhanced

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conveyance efficiency and increased the flexibility of the water supply, farmers have adopted more efficient on-farm irrigation systems, such as sprinkler or drip systems that have resulted in higher water productivity. In this line, Lecina et al. (2010) determined a 40 % increase in water productivity after sprinkler irrigation systems were adopted in the Riegos del Alto Aragón irrigation project (Spain). However, many authors have reported that after improving conveyance efficiency and adopting more efficient irrigation systems, consumptive water use has increased as a result of greater water use efficiency, higher productivity and increased evapotranspiration (Lecina et al. 2010; Dumont et al. 2013). Moreover, the energy demand has also risen considerably due to the pressure requirements of these new irrigation systems (Rodríguez Díaz et al. 2011).

In addition to higher energy consumption, the price of this input has also increased considerably over the past few years. In Spain, for example, the price of energy for irrigation has risen due to both the liberalization of the electricity market since 2003 and the elimination of special irrigation rates in 2008, thus leading to higher power and energy costs. In the liberalized electricity market, users (farmers or irrigation districts) can purchase energy directly in the daily market or obtain energy through a bilateral agreement with energy producers, which is the most frequent option (Rocamora et al. 2012). Due to this higher demand for energy and increased energy prices, Rodríguez Díaz et al. (2012a) found that management, operation and maintenance costs are almost fivefold higher after the network modernization of an irrigation district located in southern Spain. As a result, farmers' profits are falling since they have to pay the amortization costs of the modernization of both their water distribution networks and on-farm irrigation systems (Rodríguez Díaz et al. 2012). Similar trends have also been observed in other countries such as South Africa, where electricity tariffs increased by 31 % from 2009 to 2010 and are expected to increase by 25 % over the next three consecutive years (Brazilian et al. 2011).

Several authors have noted these higher energy requirements and have proposed measures to reduce them. Some of these measures have been based on the implementation of energy audits in irrigation districts (Abadía et al. 2012), sectoring (Carrillo Cobo et al. 2011; Fernández García et al. 2013), critical points control (Rodríguez Díaz et al. 2012b), or the improved management of pumping stations (Moreno et al. 2007; Lamaddalena and Khila 2012).

Sectoring and critical points control strategies may lead to significant energy savings. When sectoring, farmers are organized into irrigation turns according to their energy demand. Taking into account the network operation by sectors, Carrillo Cobo et al. (2011) estimated an energy saving of 9 and 27 % in two case studies in southern Spain, while Jiménez-Bello et al. (2010) found potential energy savings

of 36 % for a water user association located in Valencia (Spain). Regarding critical points control (hydrants with high energy requirements), Rodríguez Díaz et al. (2012b) reported energy savings of around 10 and 30 % in two irrigation districts located in southern Spain. To apply sectoring and critical points control strategies in irrigation networks with several supply points, Fernández García et al. (2013, 2014) developed methodologies based on heuristic techniques which led to energy savings of between 29 and 36 %.

The above studies, however, estimated energy costs assuming an average energy price but did not consider the electricity tariff structure. Until 2014, the electricity tariffs for high-voltage distribution in Spain were structured into 3 or 6 periods that varied according to the hour of the day and the day of the year. In July 2014, the 3-periods electricity tariff disappeared, leaving only the 6-periods tariff with some changes in the period distribution (BOE 2014). The electricity tariff includes two terms: one related to energy consumption and another that considers the power absorbed, with different prices according to the period. The average price of the power term alone increased by 288 % from 2008 to 2014 (MINETUR 2008, 2014), and its impact on the electricity bill continues to grow.

In this paper, we incorporate the electricity tariff in the sectoring and critical points control strategies developed by Fernández García et al. (2013, 2014). The aim is to analyze and compare possible network operation scenarios that take into account the electricity tariff in order to determine the minimum cost of electricity and ensure pressure requirements at hydrants.

Methodology

Study area

The study was conducted in the Palos de la Frontera irrigation district (PF) located in Huelva (southern Spain) (Fig. 1). The annual average rainfall in this area is 490 mm, and the average reference evapotranspiration is 1145 mm (Pérez Urrestarazu et al. 2009). Strawberry is the main crop and covers 75 % of the irrigated area (3343 ha). Coinciding with the period of maximum strawberry production, April and May are the most water-demanding months (Fig. 2). The PF irrigation network is a multi-source network consisting of 513 pipes and 227 hydrants fed by three pumping stations. Each hydrant is designed to supply $1.2 \times 10^{-3} \text{ m}^3 \text{ s}^{-1} \text{ ha}^{-1}$ with a service pressure of 30 m. The maximum delivery capacity of each pumping station is 1584, 1056 and 1372 L s^{-1} with a pressure head of 85, 45 and 55 m, respectively.

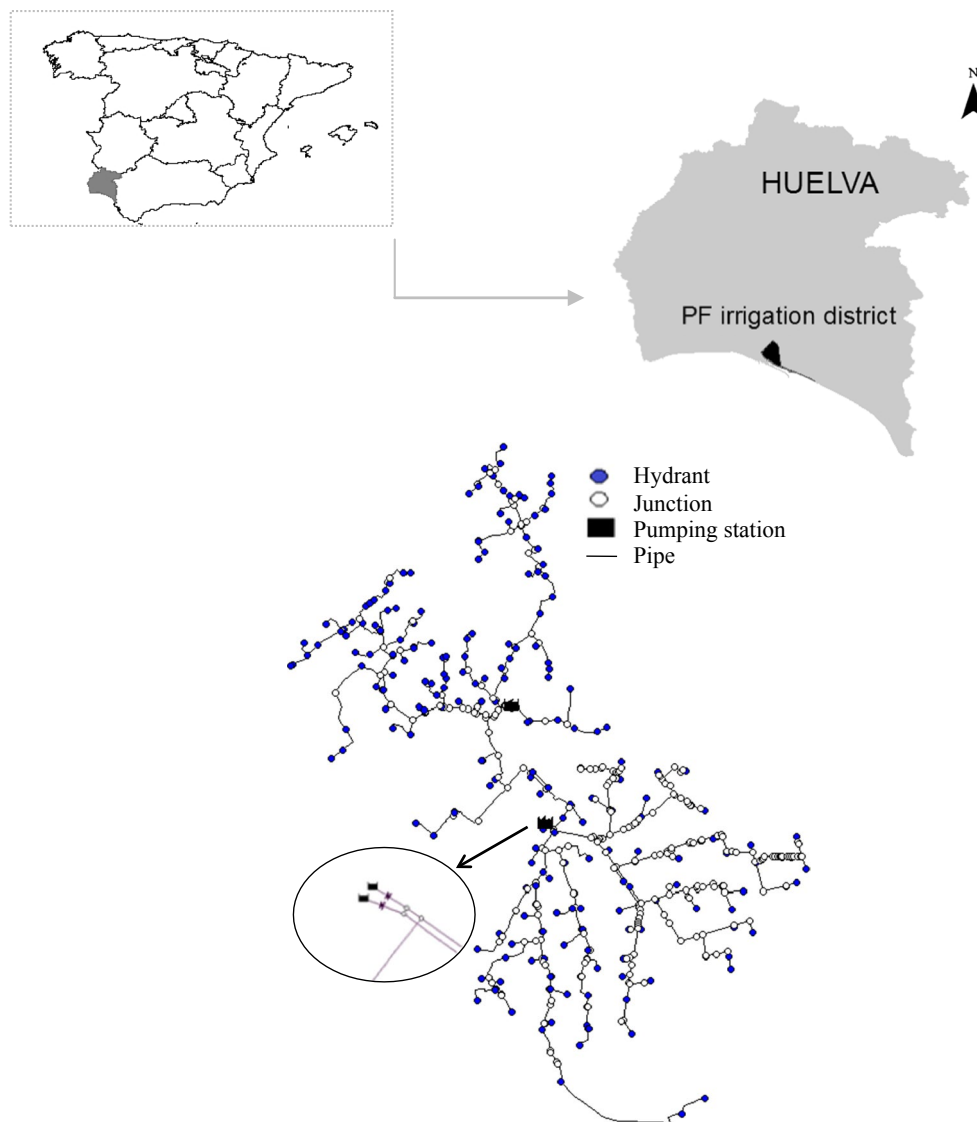


Fig. 1 Location of PF irrigation district and schematic representation of PF irrigation network

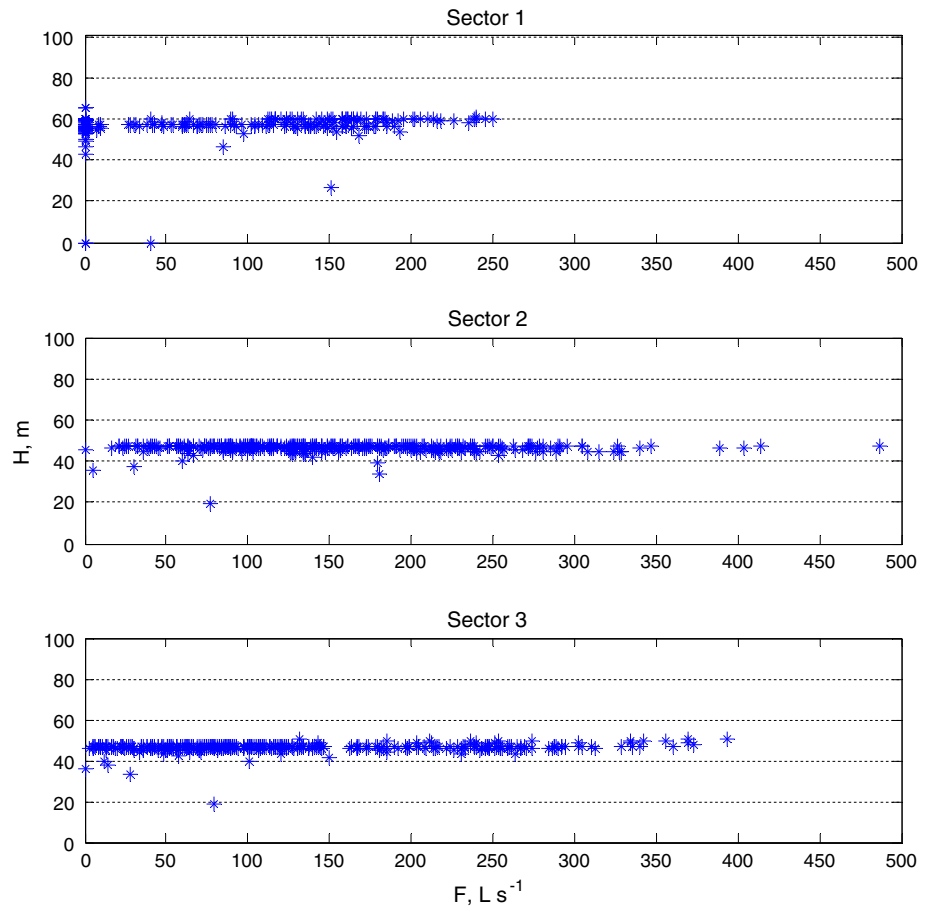
The PF irrigation district contracts the 6-period electricity tariff at a cost of €287,724 per annum. The irrigation network is currently organized into three sectors: the pressure head for sector I operation is higher than for sectors II and III, although higher flows are supplied to these sectors than to sector I (Fig. 2). Sector I has one energy counter, while only one energy counter is available for sectors II and III. The total power installed in the three pumping stations is 4800 kW.

Water and energy use optimization combined with energy cost minimization

To optimize irrigation water use and energy cost and consumption, we have developed the Water, Energy and Cost Optimization (WECO) algorithm that incorporates

a module comprising the electricity tariff into the Water and Energy Based Sectoring Operation for Multiple Supply Sources (WEBSOM) algorithm proposed by Fernández García et al. (2013) and the Water and Energy optimization by Critical Points control for Multiple supply sources (WECPM) algorithm (Fernández García et al. 2014). The WEBSOM algorithm aims at minimizing both energy consumption and pressure deficits at hydrants in pressurized multi-source irrigation networks considering operation by sectors. This algorithm enables determining the number of sectors to operate in each month and the optimal pressure head in the pumping stations according to the operating sector and month. The objectives pursued by WECPM are the same as those of WEBSOM (minimization of energy consumption and pressure deficit at hydrants). Unlike WEBSOM, however, WECPM takes into account critical

Fig. 2 Flow–Head histogram of the three sectors and monthly crop water requirements (IN)



points control. This methodology permits detecting critical points and identifying measures to improve the operation of these hydrants. The monthly optimal pressure head in the pumping stations is determined at a hydrant simultaneity rate of 100 %.

WECO therefore enables achieving the optimal operation of an irrigation network by taking into account the minimization of both energy costs and pressure deficits at hydrants, while ensuring crop water requirements.

Genetic algorithms (Goldberg 1989) are heuristic techniques which are widely applied to many optimization problems of water distribution systems (Montesinos et al. 1999; Reca et al. 2008; Jiménez-Bello et al. 2010; Fallah-Mehdipour et al. 2012). These algorithms provide a set of optimal solutions for a given optimization problem by optimizing a single objective function. However, many decision-making problems need to achieve several conflicting objectives (Savic 2007). In a multiobjective approach, the set of optimal solutions are known as the Pareto frontier, which provides solutions for two or three objectives. WEBSOM and WECPM were developed using the NSGA-II multiobjective algorithm (Non-dominated Sorting Genetic Algorithm) (Deb et al. 2002) because of its successful

application in the optimization of this type of problem (Farmani et al. 2006; Consoli et al. 2008).

The WECO algorithm links WEBSOM and WECPM by means of the electricity tariff module to analyze and compare the following optimal network operation scenarios:

- Scenario 1. Operation of the irrigation network by sectors, establishing monthly irrigation turns for each sector.
- Scenario 2. Irrigation network operation without sectors, considering 100 % demand simultaneity.
- Scenario 3. Operation of the irrigation network without sectors (100 % demand simultaneity) and considering improvement actions after identifying critical points.
- Scenario 4. Implementation of improvement actions in the identified critical points and network operation by sectors.

Because WECO enables comparing and determining which operation scenario achieves the highest economic savings, these scenarios were established to offer feasible energy optimization strategies to irrigation district managers; WECO was implemented in MATLAB™ (Pratap

2010) using EPANET as a hydraulic simulator (Rossman 2000).

Electricity tariff module

Electricity tariff data are stored in the module in order to integrate the data into the network operation scenarios. The structure of the electricity tariff is strongly related to the electricity market and regulations of each country. Users are commonly offered two types of tariff schedules: one with a flat rate in which the same energy price is considered all day and another with different prices according to the time energy is consumed. These time-of-use tariffs consider different periods, each one with a specific energy price. The number and lengths of the periods can vary according to the day. Normally, peak demand periods result in higher electricity rates, while off-peak periods entail lower energy prices.

Irrigation districts often contract time-of-use tariffs. Thus, for a certain tariff, the annual electricity cost (€ year⁻¹) is obtained by summing two terms: a fixed cost concerning the contracted power (EICo_{fix}) and a variable cost linked to the energy consumption (EICo_{var}), both of which are related to the energy price in each period:

$$EICo = EICo_{fix} + EICo_{var} \tag{1}$$

EICo_{fix} (Eq. 2) and EICo_{var} (Eq. 3) are determined as follows:

$$EICo_{fix} = \sum_{p=1}^{np} Power_{maxp} \cdot Ppower_p \tag{2}$$

where p is the period index, np is the number of periods, $Power_{maxp}$ is the contracted power according to the maximum absorbed value in period p (kW year⁻¹), and $Ppower_p$ is the power term price in period p (€ kW⁻¹).

$$EICo_{var} = \frac{1}{1000} \cdot \frac{1}{\eta} \cdot \gamma \cdot \sum_{d=1}^{nd} \sum_{w=1}^{nsect} \sum_{p=1}^{np} \times t_p \cdot Pec_p \sum_{i=1}^N (Q_{ipwd} \cdot H_{ipwd}) \tag{3}$$

where d , w , and i are the day index, the sector index, and the pumping station index, respectively, nd is the number of operation days, n_{sect} is the number of possible sectors (when the network is operated by sectors), N is the number of pumping stations, η is the global efficiency of pumps, γ is the water specific weight (9800 Nm⁻³), t_p is the daily irrigation time (h) during period p , Pec_p (€ kWh⁻¹) is the energy price according to period p , and Q_{ipwd} (m³ s⁻¹) and H_{ipwd} (m) are the pumped flow and the pressure head supplied by station i during period p when sector w operates

during day d . In Eq. 3, all hydrants associated with a certain sector are operated simultaneously during the time required to satisfy crop irrigation needs (estimated by Allen et al. 1998).

Using this general tariff, the annual electricity cost can be obtained for a wide range of real cases.

Network operation scenarios

- Scenario 1

This scenario is evaluated with WEBSOM linked to the electricity tariff module. Firstly, hydrants are grouped into sectors according to two dimensionless topological coordinates that relate hydrant elevation and distance from the pumping stations. Depending on the network topology, hydrants may be classified into 2 to n_{sect} sectors. WEBSOM establishes an optimum sectoring calendar based on minimum energy costs and minimum irrigation and pressure deficits. Thus, the optimum number of irrigation sectors varies by month.

The customized NSGA-II proposed by Fernández García et al. (2013) was applied after including several modifications related to the generation of the initial population and the objective functions as follows:

Initial population

In this case, the number of variables of each chromosome, n_v , was obtained as follows:

$$n_v = N \cdot n_{sect} \cdot n_d \tag{4}$$

Objective functions

The following objective functions, determined for each month of the irrigation season, were minimized:

$$F1_{sce1} = EICo_{varnorm} + CID_{norm} \tag{5}$$

$$F2_{sce1} = \max [a \cdot Pf_w + b \cdot CMPD_{normw}]_{w=1}^{nsect} \tag{6}$$

where $EICo_{varnorm}$ is the normalized total energy cost, and CID_{norm} is the normalized maximum irrigation deficit obtained from the daily difference between the theoretical crop irrigation requirements (estimated according to Allen et al. 1998) and the flow supplied by all pumping stations (Fernández García et al. 2013). Both terms were normalized by the distribution U (0.1) to perform their summation. $EICo_{varnorm}$ and CID_{norm} varied from 0 to 1. Therefore, the minimum and maximum values of $F1$ were 0 and 2, respectively.

In Eq. 6, Pf_w is the pressure failure percentage which ranged from 0 (all hydrants get the service pressure) to 1 (all hydrants get a pressure lower than the service

pressure), and $\text{CMPD}_{\text{norm}_w}$ is the normalized term that evaluates the monthly magnitude of the pressure deficit (Fernández García et al. 2013). a and b are coefficients with values 0.5 and 1.5 to penalize solutions with an increased CMPD_w term. In irrigation districts, slight pressure deficits in several hydrants can be easily assumed, whereas a significant pressure deficit in only one hydrant hinders the proper operation of the network. Pf_w and CMPD_w were calculated for all operating sectors on a given day. The value of $F2_{\text{sce}1}$ was the maximum value obtained by summing these terms for each sector. The minimum and maximum values of $F2_{\text{sce}1}$ were 0 and 2, respectively.

Given that the minimal value of the term ElCo_{var} depends on the optimal combination of $Q_{1\text{wks}}$, $H_{1\text{wks}}$, and Pec_p , in the first phase, the daily power demand of the operating sectors was determined. The sectors were then sorted in descending order of power demand, and the electricity tariff periods were sorted in increasing order of energy price (Pec_{np} , Pec_{np-1} , ..., Pec_1). Starting with the most power-demanding sector, if the daily time required to satisfy crop irrigation requirements (t_{rs}) was lower than the number of hours of the upper period (t_{np}), the energy cost of this sector was determined by multiplying its power demand by the term t_{rs} and by Pec_{np} . In contrast, if t_{np} was lower than t_{rs} , the energy cost in this period of the sector was calculated by multiplying its power demand by t_{np} and by Pec_{np} . The remaining hours ($t_{rs}-t_{np}$) were assigned to the next tariff period ($np-1$), and the energy cost of this sector in this period was obtained by multiplying the power demand by (t_s-t_{np}) and by Pec_{np-1} . Therefore, the energy cost of the aforementioned sector was the sum of the energy costs obtained in each period. The energy cost of the following operating sectors was calculated by the same procedure but starting in the tariff period in which the previous power-demanding sector finished. When t_{rs} was greater than the water availability time according to sectoring option (t_a), the irrigation requirements were not fully satisfied (Fernández García et al. 2013).

- Scenario 2

This scenario can be evaluated with the WECPM algorithm linked to the electricity tariff module to determine both the minimum energy cost and the pressure deficit. The crop water requirements were indirectly considered in the calculation of the energy cost since the pumped flow (Eq. 3) matched the volume of water required to satisfy crop irrigation needs. The optimal pressure heads in pumping stations when all hydrants operate simultaneously can be obtained with this algorithm. The NSGA-II algorithm has been adapted to the current problem:

Initial population

The number of variables of each chromosome, n_v , was determined as follows:

$$n_v = N \cdot n_d \quad (7)$$

Objective functions

The objective functions stated in Eqs. 5 and 6 were minimized. In this case, however, the term CID_{norm} was 0 in all cases because WECPM does not consider sectoring operation and the irrigation time required to meet crop water demand is always reached.

The electricity tariff module was integrated in this scenario as follows: On a given day, irrigation started in the period with the lowest energy price, np . If t_{rs} was lower than t_p , the daily energy cost of the network operation was obtained by multiplying the power demand by t_{rs} and by Pec_{np} . In contrast, when t_{rs} was greater than t_p , irrigation occurred over several tariff periods. Therefore, the energy cost in np period was calculated by multiplying the power demand by t_p and by Pec_{np} . The energy cost in the following tariff period, $np-1$, was determined by multiplying the power demand by ($t_{rs}-t_p$) and by Pec_{np-1} . Hence, the daily energy cost was the sum of the energy costs obtained in each period.

- Scenario 3

In this case, the optimization process described in scenario 2 was applied but considering the proposed energy saving actions to control the critical points identified in the network (Fernández García et al. 2014). These improvement measures required changes in pipe sizes and the installation of booster pumps.

- Scenario 4

The WECPM and WEBSOM algorithms were sequentially applied in combination with the tariff module to determine the minimum energy cost when the irrigation network was managed by sectors and the measures to improve the operation of critical points were implemented. The process to detect and control the critical points was carried out by WECPM followed by the application of WEBSOM.

Results and discussion

The proposed scenarios were evaluated in the PF irrigation network assuming a pumping efficiency of 0.8. In this case, we only analyzed how the electricity tariff affected the

Table 1 Number and value of variables of the optimization process for each scenario

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	$N = 3$	$N = 3$	$N = 3$	$N = 3$
	$n_{\text{sect}} = 5$			$n_{\text{sect}} = 5$
n_v				
June	45	9	9	45
Rest of months	30	6	6	30

optimal number of operating sectors and energy consumption. However, the methodology can be easily adapted to include the real efficiency of the pumping stations and even the effects of installing variable speed drives. As strawberry (with the largest irrigated area) is a low water stress tolerant crop, the irrigation deficit term (CID_{norm}) was 0 when there was no irrigation deficit and 1 when the flow supplied by all the pumping stations was 5 % lower than the theoretical crop irrigation requirements (Q_{req}). Irrigation deficits higher than 5 % of Q_{req} were penalized with values of 2 and 1.9 for the first ($F1$) and second objective functions, respectively. These values (2 and 1.9) were assumed since lower values could imply the removal of possible solutions to the optimization problem, while the value of 2 was assigned to unfeasible solutions that could be generated during the optimization process for both objective functions.

As regards the algorithm parameters, 50 individuals and 100 generations and crossover and mutation probabilities of 0.9 and 0.1, respectively, were established for the four scenarios. Table 1 shows the number of variables in each scenario. The values of the total head of the three pumping stations were 0 (the pumping stations were not operating) or a random number between 45 and 95 m, the operational range of the pumping stations.

Effects of the electricity tariff

The 6-periods Spanish tariff of 2009 was applied to the PF irrigation district since the contracted power exceeded 450 kW (Spanish Ministry of Economy 2001). The period distribution throughout the year followed the schedule established by the government before the current period distribution scheme published in July 2014 (BOE 2014). However, the methodology shown in this work can be easily adapted to different period distributions. Period 1 (P1) is the most expensive, and the price of both energy and power falls progressively until reaching P6, the lowest price period. Two different types of days, working days and weekends, are proposed in each month in this tariff except in June, in which three different types of days (first and second half and weekends) were considered. Hence, we optimized the annual cost (energy and power cost) taking into

account two different types of days in every month (three in June). Weekends are charged according to P6 (Fig. 3).

The electricity tariff structure particularly affected the network operation by sectors since irrigation in turns involved up to 19 h of operation (Table 2). Thus, irrigation in expensive hours could occur.

When the electricity tariff was included in the analysis, the optimal number of sectors differed from those obtained in the original WEBSOM model. Furthermore, two sectoring options per month (three in June), working days and weekends, were obtained after including the electricity tariff. Table 3 compares the optimal sectors operation calendar obtained by Fernández García et al. (2013) and the new calendar obtained for scenarios 1 and 4. Using WEBSOM without the energy tariff, five sectors could operate in June and October. When the electricity tariff was considered, the maximum number of operating sectors (working days) was four in scenario 1, and five (December) in scenario 4.

Moreover, the number of sectors operating on working days in the peak water demand months (greatest t_{rs}) of April and May was lower because the larger the number of operating sectors, the greater the irrigation time in expensive hours. Thus, energy costs can be higher if the number of operating sectors increases. To highlight how the electricity tariff influences energy consumption and operational costs, Table 4 shows the values associated with two possible solutions derived from scenario 1 in March, October, and November. Solution 1 showed energy consumptions lower than solution 2 in those months. However, the energy costs associated with solution 1 were higher than those of solution 2. This effect can be explained by observing the number of operating sectors (working days) in both solutions. The number of sectors was higher in solution 1 (the solution with the lowest energy consumption) than in solution 2, thus indicating that the network was operating during expensive hours and that the energy costs were higher. This seems to indicate that the electricity tariff structure does not reduce energy consumption.

Casado (2012) studied water and energy management in an irrigation district of southern Spain with a network that operated only in period P6 in the 2009/2010 irrigation season. He reported a reduction in energy costs in 2009/2010 over 2008/2009 (when there was no demand concentration in P6). However, energy consumption between both irrigation seasons increased because the hourly peak demand and higher pumped flows reduced the pumping efficiency and caused higher friction losses in pipes. In a similar line, Rocamora et al. (2012) reported that the proper selection of the energy contract may increase economic efficiency but not necessarily energy efficiency.

The incorporation of the electricity tariff module has permitted obtaining a realistic and optimum sectoring calendar which provides the scheduling and operation

						1-15	15-30						
Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
00-01	1	3	1	1	1	1	1	3	1	3	1	1	
01-02	1/3	3	1	1	1	1	1	3	1	3	1	1/3	
02-03	3	3/1	1	1	1	1	2	3	1	3	1/3	3	
03-04	3/2	1	1	1	1	1/2	1/3	2	3	1	3	3	2
04-05	2	1	1/3	1	1	2	3	3/1		3/1	3/4	2/4	
05-06	2	2	3	1	1	2	3	1		1	4	4	
06-07		2	3	1	1	2	3	1		1	4/2		
07-08		2	3		1		2	1		1	2		
08-09			3		1		2	1/2		1	2		
09-10			3/4		1		2	2		1/2			
10-11			4					2		2			
11-12			4					2		2			
12-13			4					2		2			
13-14			4					2		2			
14-15			4/2							2			
15-16			2										
16-17			2										
17-18			2										
18-19													
19-20							2/4						
20-21							4						
21-22							4						
22-23			2				4						
23-24			2										
Period	Energy price, c€ kWh ⁻¹					Power Price, c€ kW ⁻¹							
P6	6.99					169							
P5	9.33					370							
P4	9.97					370							
P3	11.03					370							
P2	11.37					505							
P1	13.18					1009							

Fig. 3 Periods (colored cells indicate the periods) and energy and power price in the 6-period tariff (for the 2009 irrigation season) and scheduling of operating sectors (working days), from sector 1 to sector 4 (numbers in cells), in scenario 1

Table 2 Operation hours per day in each scenario

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
January	5.1	1.7	1.7	5.1
February	7.5	2.5	2.5	7.5
March	19.2	4.8	4.8	4.8
April	6.7	6.7	6.7	6.7
May	9.5	9.5	9.5	9.5
June	7/14 ^a	3.5/3.5 ^a	3.5/3.5 ^a	3.5/3.5 ^a
July	4	2	2	6
August	13.2	4.4	4.4	13.2
September	3.9	3.9	3.9	11.7
October	14.1	4.7	4.7	14.1
November	8.8	2.2	2.2	6.6
December	6	1.5	1.5	7.5

^a Operation hours in second half of June

sequence of the sectors during the day according to their power demand and the energy cost (Fig. 3). When the

network was managed without sectors (scenarios 2 and 3), the electricity tariff established an irrigation schedule that was concentrated in the lowest price periods.

Scenario comparison

Figure 4 shows the Pareto frontier obtained in each scenario for the peak water demand month (May). As expected, the lowest values of *F1* were associated with the highest values of *F2*. In order to compare the scenarios, the minimum value of one of the objective functions was fixed in all scenarios and the values of the other objective function were then compared. In this case, we decided to fix the minimum value of *F2* since the minimum value of *F1* in scenarios 1, 2 and 4 involved unacceptable pressure deficits.

In scenario 1, the adopted solution (square marker) had *F1*_{sce1} and *F2*_{sce1} values of 1.43 and 0.02, respectively. However, another solution (S2) in the Pareto frontier had *F1*_{sce1} and *F2*_{sce1} values of 0.60 and 0.06, respectively. A priori, S2 seemed to be better than the selected solution.

Table 3 Optimal sectors operation calendar obtained by the original WEBSOM (A), WECO scenario 1 (working days and weekends) (B), and WECO scenario 4 (working days and weekends) (C)

	January	February	March	April	May	June	July	August	September	October	November	December
t_{rs}	1.7	2.5	4.8	6.7	9.5	3.5	2.0	4.4	3.9	4.7	2.2	1.5
A	2	2	3	3	2	5	3	2	4	5	4	3
B	3/3	3/5	4/5	1/3	1/3	2/4/4 ^a	2/3	3/2	1/4	3/4	4/4	4/3
C	3/5	3/3	1/4	1/3	1/1	1/1/4 ^a	3/3	3/5	3/4	3/4	3/4	5/5

^a The first, second, and third values are associated with the first half, second half and weekends of June

Table 4 Energy consumption, EC (MWh month⁻¹); energy cost, ElCo (€ month⁻¹); and operating sectors (in working days) in two possible solutions obtained in scenario 1

	Solution 1			Solution 2		
	EC (MWh)	ElCo (€)	Sectors	EC (MWh)	ElCo (€)	Sectors
March	327	25,837	4	346	25,040	2
October	253	19,012	3	257	18,553	2
November	110	7799	4	111	7771	3

Fig. 4 Pareto frontier: $F1$ (objective function 1) versus $F2$ (objective function 2) obtained for May in each scenario

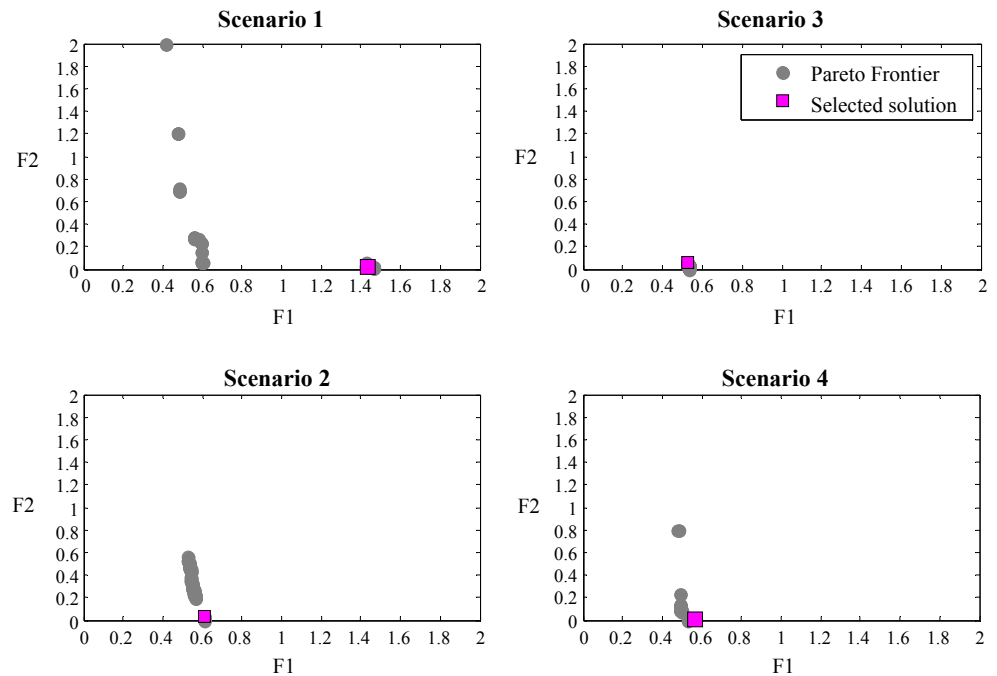


Table 5 Values associated with the selected Pareto frontier solution in May

	S1	S2	S3	S4
ElCo (€ month ⁻¹)	52,791	54,670	47,524	55,405
Energy consumption (MWh month ⁻¹)	728	754	656	768
ID (% of Q_{reqMay})	5	–	–	–
Number of critical hydrants (working days)	–	–	4	–
Number of critical hydrants (weekends)	–	2	–	–
Pressure in the critical hydrant (working days), m	30	30	29	30
Pressure in the critical hydrant (weekends), m	30	29	30	30

Table 6 Energy consumption, energy cost (operation costs and amortization costs of improvement actions), contracted power and power cost in each scenario

	Energy consumption (MWh)				Energy cost (€)			
	S1	S2	S3	S4	S1	S2	S3	S4
January	93	102	97	86	6484	7142	6807	5983
February	122	131	127	115	8496	9153	8886	8007
March	327	354	318	313	25,837	24,756	22,245	21,909
April	512	512	433	455	35,809	35,791	30,281	31,801
May	728	754	656	768	52,791	54,670	47,524	55,405
June	270	289	229	283	19,912	20,183	15,997	19,778
July	20	23	21	20	1388	1621	1469	1363
August	58	67	62	57	4032	4685	4321	3977
September	314	304	264	252	21,949	21,237	18,473	18,554
October	253	284	275	242	19,012	19,840	19,193	18,145
November	110	127	124	108	7840	8884	8688	7529
December	79	91	92	77	5504	6331	6401	5353
Total energy	2885	3037	2698	2774	209,054	214,294	190,284	197,805
Amortization costs					–	–	1895	1895
	Contracted power (kW)				Power cost (€)			
	S1	S2	S3	S4	S1	S2	S3	S4
P6	2650	2920	2410	3460	4479	4935	4072	5847
P5	2540	2600	2180	2270	9398	9620	8066	8399
P4	530	200	200	370	1961	740	740	1369
P3	400	200	200	200	1480	740	740	740
P2	380	200	200	200	1919	1010	1010	1010
P1	200	200	200	200	2018	2018	2018	2018
Total power cost					21,255	19,063	16,647	19,383
Total electricity cost					230,309	233,357	208,826	219,083

Nevertheless, the terms $EICovar_{norm}$ and CID_{norm} in the chosen solution were 0.53 and 0.91, while these terms were 0.59 and 0.01 in S2, thus implying higher energy demand (814 MWh and €59,027 compared to 728 MWh and €52,791 in the selected solution) but a similar quality of service.

Table 5 reports the values of energy cost, energy consumption, irrigation deficit, pressure in the critical hydrant and number of critical hydrants (hydrants with pressure lower than the service pressure) associated with each selected solution (square marker) of the Pareto frontier plotted in Fig. 4. The improvements in scenarios 3 and 4 consisted of replacing 442 m of pipes and installing three booster stations (one of them supplied two critical points) (Fernández García et al. 2014). The investment costs and energy cost of operating the booster pumps were also included in the analysis of these scenarios. The investment costs amounted to €13,951, while the annual cost (€1895) was determined considering a payback period of 10 years and an interest rate of 6 % (Table 6). Thus, the annual cost per hydrant was estimated at €8.35.

Scenario 3 achieved the lowest energy consumption and cost although a slight pressure deficit (only 1 m) was observed in four hydrants on working days in May. However, this pressure deficit could be acceptable for farmers since a pressure of 29 m is sufficient for drip irrigation systems.

The highest energy consumption and operational costs were obtained in scenario 2 although it should be noted that this scenario determined the optimal pressure heads in the pumping stations and did not consider measures such as sectoring or critical points control. However, this scenario has wider applicability because investment costs and the establishment of irrigation turns are not necessary.

Comparing monthly energy consumption, scenario 1 achieved lower values than scenario 3 in January, February, July, August, October, November, and December. However, in March, April, May, June, and September, the months with the highest instantaneous water demand, scenario 3 was better (Fernández García et al. 2014). Likewise, scenario 3 achieved lower energy consumption than scenario 4 in April, May, and June. However, unlike scenario 1,

scenario 4 performed better than scenario 3 in March and September.

As regards the cost of energy, scenario 3 achieved the lowest energy cost, which increased gradually in scenarios 4 (4 %), 1 (9 %) and 2 (11 %). However, scenarios 1 and 4 showed lower monthly energy costs than scenario 3 in off-peak months. On the other hand, considering that the actual energy cost in this irrigation district is €287,724, all scenarios achieved significant energy cost savings, from scenario 2 with an energy cost savings of 26 % to scenario 3 with an energy cost savings of 34 %.

Additional economic savings related to contracted power

The four scenarios analyzed by the WECO algorithm considered the simultaneous operation of hydrants, thus permitting the maximum power demand in each tariff period to be determined. This information is key to adjusting the fixed term in Eq. 1, the contracted power. In Spain, the contracted power must be at least equal to the maximum power demand in each tariff period to avoid cost penalties. For this reason, irrigation districts often contract a value of power that is higher than the strictly required value, therefore increasing the cost of power. WECO provided the optimized value of power demand, and hence the recommended values of the contracted power for the different periods. The maximum power requirements occurred in period P6: 2650, 2920, 2410, and 3460 kW in scenarios 1, 2, 3, and 4, respectively (Table 6). These values were significantly lower than the contracted power of 7522 kW indicated by Rodríguez Díaz et al. (2011) for this irrigation district in this tariff period. The annual power cost in each scenario is shown in Table 6. The lowest power cost was achieved in scenario 3, with this cost increasing gradually in scenarios 2, 4, and 1. Scenario 1 showed the highest cost since power was contracted in all periods, except in period P1. In scenario 4, power was contracted in periods P6, P5, and P4, while in scenarios 3 and 2 power was contracted in periods P6 and P5, the periods with the lowest power prices. In the tariff periods in which the irrigation network did not operate, a minimum power of 200 kW was contracted to maintain the facilities (Casado 2012).

These results suggest that the strategy that best minimizes electricity costs—both the energy cost (also the minimum energy consumption) and the power cost—could be a combination of scenarios 3 and 4 during the irrigation season. According to these results, measures to improve the critical hydrants should be taken so that all the hydrants can irrigate at the same time in April, May, June, and September, while the irrigation network should be operated in sectors in the remaining months. Thus, the annual energy consumption would be 2598 MWh and the energy

cost €184,541. This would lead to an additional reduction of 100 MWh (3 %) in energy consumption as well as a €5743 (3 %) reduction in energy costs with respect to scenario 3 (the scenario with the lowest energy consumption and cost). The contracted power would be the same as that proposed in scenario 3, and the resulting power cost would be €16,647. Therefore, taking into account the energy and power cost and the amortization cost, the total electricity cost associated with this strategy would be €203,083.

Conclusions

The higher energy requirements in pressurized irrigation networks and the increase in energy prices have significantly reduced farm profits.

The WECO algorithm provides the optimal operation of irrigation networks by minimizing both energy costs and pressure deficits at hydrants according to different scenarios: All the hydrants in the network work simultaneously, or the network is operated by sectors with or without critical points control. The WECO algorithm upgrades the previous models (WEBSOM and WECPM) by including the electricity tariff structure to determine irrigation scheduling with the minimum total electricity cost according to the price of energy and power in each tariff period.

The algorithm has been applied to a real irrigation network. The minimum annual cost in the network was achieved for operation without sectoring that considers measures to improve the operation of critical points. However, if the energy cost analysis is carried out per month, the sectoring operation combined with measures to ameliorate the hydraulic behavior of the critical hydrants performs better in months with low irrigation requirements. Thus, if measures to control the critical points are assumed and two network operation strategies are adopted (all hydrants operating simultaneously in peak energy demand months and hydrants grouped into sectors in the others), an additional reduction in energy costs can be achieved.

Incorporating the electricity tariff module implies the optimization of energy costs but not necessarily the optimization of energy consumption, particularly when the network is managed by sectors. When this is the case, with more operating sectors the network operation time and the likelihood of irrigation in the most expensive hours augment. To fit the network operation to cheap energy periods, a lower number of irrigation turns is established, which involves higher energy consumption in some cases.

WECO also enables the optimization of the contracted power. This is the fixed term of the electricity tariff that can lead to significant economic savings when properly selected and provide optimal irrigation scheduling with the lowest electricity cost per year.

WECO is a decision-making support system that can analyze alternative irrigation network operation scenarios. Water managers and farmers can choose the scenario according to their preferences: from the simplest applicable scenario in which only the pressure heads in the pumping stations are optimized, thus involving small economic savings, to another scenario entailing improvements at critical points and irrigation scheduling in turns that can lead to the lowest operation and power costs.

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