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The role of energy audits in irrigated areas. The case of 'Fuente Palmera' irrigation district (Spain)

M. T. Carrillo-Cobo[1], J. A. Rodriguez-Diaz[1]* and E. Camacho-Poyato[2]

[1] *Department of Agronomy. University of Córdoba. Campus Rabanales. Edif. da Vinci. 14071 Córdoba. Spain*
[2] *Department of Rural Engineering. University of Córdoba. Campus Rabanales. Edif. da Vinci. 14071 Córdoba. Spain*

Abstract

In recent years, energy consumption for irrigation has grown rapidly. Actually, nowadays energy represents a significant percentage on the total water costs in irrigation districts using energy to pressurize water. With the aim of improving energy efficiency in the Fuente Palmera irrigation district, was applied the protocol for conducting energy audits in irrigation districts developed by Spanish Institute for Diversification and Energy Savings (IDAE). The irrigated area organized in two independent sectors according to a homogeneous elevation criterion is analyzed and simulated. The potential energy savings derived from this measure was evaluated. For this purpose, a model based on the hydraulic simulator EPANET has been carried out. Its energy demand was estimated in 1,360 kWh ha^{-1} and its overall energy efficiency in 56%. The district was globally classified in group C (normal). Results show potential energy savings of up to 12% were obtained when the network was divided in sectors and farmers organized in two irrigation shifts. Further energy savings could be achieved by improving the hydraulic structures, such as the pumping station or the network layout and dimensions.

Additional key words: energy efficiency; pressurised irrigation networks; water management; water supply systems.

Resumen

La importancia de las auditorías energéticas en zonas regables. El caso de la zona regable de Fuente Palmera (España)

En los últimos años, el consumo de energía en el regadío ha crecido de forma significativa. De hecho, hoy en día la energía representa un importante porcentaje de los costes totales del agua en las comunidades de regantes que usan energía para presurizar el agua. Con el objetivo de mejorar la eficiencia en el uso de la energía en la Comunidad de Regantes de Fuente Palmera, se ha aplicado el protocolo para la realización de auditorías energéticas, elaborado por el Instituto para la Diversificación y Ahorro de Energía (IDAE). Se ha analizado y simulado los ahorros potenciales de energía alcanzados si se reorganiza la demanda en turnos de riego, sectorizando la red en grupos de cota homogénea. Esta medida ha sido evaluada mediante el simulador hidráulico EPANET. Su demanda de energía se estimó en 1.360 kWh ha^{-1} y su eficiencia energética global en el 56%. De esta forma se clasificó la comunidad dentro del grupo C (normal). Los resultados muestran ahorros potenciales de energía hasta el 12% mediante la sectorización de la red y la organización de los regantes en dos turnos. Medidas alternativas de mejora en las estructuras hidráulicas, tales como en la estación de bombeo o en el diseño de la red alcanzarían relevantes ahorros energéticos.

Palabras clave adicionales: eficiencia energética; gestión del agua; redes de riego a presión; sistemas de suministro de agua.

* Corresponding author: jarodriguez@uco.es
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Abbreviations used: ECI (energy charge index), EDR (energy dependence rate), ER (energy required), ESE (energy supply efficiency), IDAE (Instituto para la Diversificación y Ahorro de la Energía), IE (initial energy of the water), MOM (management, maintenance and operation), OEE (overall energy efficiency), PEE (pumping energy efficiency).

Introduction

Energy consumption has continuously grown in the last decades worldwide. Because of increased energy costs, energy scarcity and energy related pollution, in the last years all economic sectors have intensified their efforts to improve energy use efficiency.

Irrigated agriculture is one of the sectors that have experienced a notable increase in energy use during recent years. In Spain, this increase is mainly due to irrigation modernization programs, where open channel distribution systems are being replaced by on-demand pressurized networks. These measures have succeeded in improving irrigation efficiency. However, they have led to a significant increase in energy consumption. Actually, Corominas (2009) reported that while water use per hectare has been reduced by 23% since 1950, energy demand has been increased by 670%.

In the last years, research efforts were devoted to the improvement of irrigation efficiency by means of benchmarking techniques and performance indicators (Malano and Burton, 2001; Rodríguez-Díaz *et al*., 2008). Recent studies have focused on the need to improve water and energy efficiency at the same time (Pulido-Calvo *et al*., 2003; ITRC, 2005; Moreno *et al*., 2007, 2009; Vieira and Ramos, 2009; Daccache *et al*., 2010). Other research works have highlighted that energy savings of up to 20% could be achieved by introducing minor changes in the irrigation district's management practices (Rodríguez-Díaz *et al*., 2009; Jiménez-Bello *et al*., 2010; Moreno *et al*., 2010).

An aggravating factor is that, due to the liberalization of the Spanish Electricity Market, on 1st January 2008 the special tariffs for irrigation disappeared and now irrigation districts have to use the same tariffs as the rest of the industry. During the months of June and July, when the peak of the irrigation demand is concentrated, most of the daily hours are included in periods of expensive tariffs.

In this context, the European Directive 2006/32/EC (OJ, 2006), on energy and energy services efficiency, established the necessity of carrying out actions to achieve energy savings of at least 9% before 2016. This objective was implemented in Spain through the «Strategy for Energy Saving and Efficiency in Spain 2004-2012 (E4)». The measures under this strategy were reflected on the Energy Action Plan for 2005-2007 (EAP 4), which set some energy saving measures. Subsequently, with the aim of meeting the Kyoto Protocol, the Action Plan E4 Plus (EAP4+), scope 2008-2012, was launched which aims to reduce emissions by 20% in 2020 (IDAE, 2007).

In the irrigated agriculture sector, two main measures are proposed in these plans. The first measure is the migration from sprinkler to drip irrigation systems, and the second is the improvement of efficiency through energy audits in irrigation districts. In this way, the Spanish Institute for Diversification and Energy Saving (IDAE, 2008) proposed a protocol for conducting energy audits, which evaluates efficiency by means of water and energy performance indicators. This methodology allows detection of inefficiencies and provides information on the required improvement actions (Abadía *et al.,* 2008).

The initial set of indicators proposed by IDAE has been extended in recent studies (Abadía *et al.,* 2009) and applied to several irrigation districts in other Spanish regions (Abadía *et al.,* 2007; Córcoles *et al*., 2008). In other works, alternative protocols for energy audits were proposed, following similar methodologies and outputs (Ederra and Larumbe, 2007).

In this work, water and energy use were evaluated at the Fuente Palmera irrigation district, using the IDAE protocol for energy audits. Alternative management measures were adopted for achieve energy savings such as sectoring the network in several sectors according to homogeneous group. This measure was analyzed on the hydraulic model EPANET and the potential energy savings derived from this measure were evaluated.

Material and methods

Study area

The Fuente Palmera irrigation district, located in Córdoba (Southern of Spain) has a total irrigated area of 5,611 ha (Fig. 1). The climate in the region is predominantly Mediterranean, with rainfall concentrated mainly in autumn and spring, and dry spells in summer. The average annual rainfall in the area is 550 mm, and the average temperature is 17.9°C. In the analyzed irrigation season (2007) annual rainfall was 523 mm and potential evapotranspiration was 1,323 mm (Carrillo-Cobo, 2009). Consequently 2007 can be considered representative of the average year (Rodríguez-Díaz, 2003). There is a wide range of crops in the district, with cereals, citrus and olives trees covering more than 60% of the area (Carrillo-Cobo, 2009).

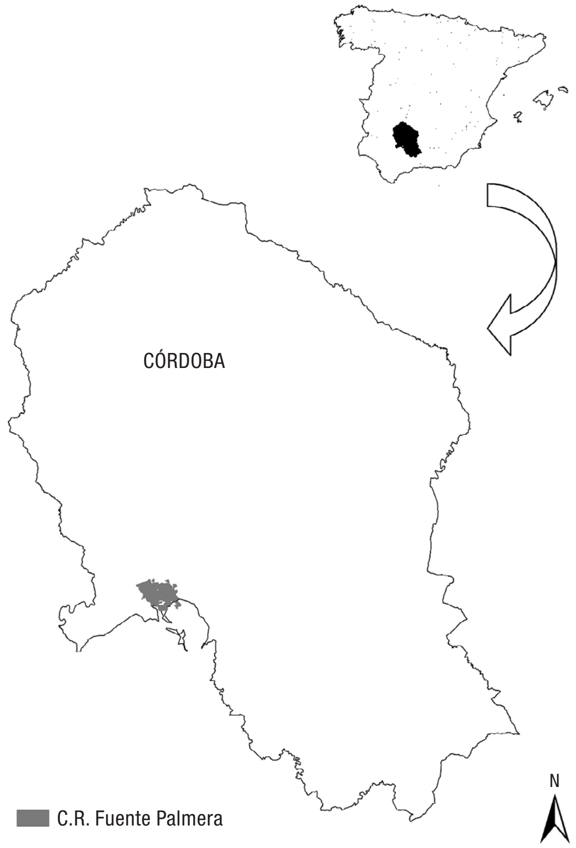

Figure 1. Location of the Fuente Palmera irrigation district with the Córdoba province and Spain.

Irrigation water is diverted from the Guadalquivir River and conveyed to an elevated reservoir through a first pumping station. At the reservoir there is a booster pumping station feeding 85 hydrants. The pressurized collective network has a total length of 45 km. It was designed to supply 1.2 L s^{-1} ha^{-1} arranged on demand, with a minimum pressure head of 30 m at every hydrant. The topography is quite steep, and hydrant elevation ranges from 86 to 165 m.

The booster pumping station (altitude of 113.9 m) is equipped with six horizontal centrifugal pumps of 1,825 kW, two of 495 kW and one of 540 kW, equipped with variable speed drives, being the total installed power 2.2 $kWha^{-1}$. The pumps are activated sequentially according to manometric regulation. The pumping station has a telemetry system which records hydraulic parameters (pressure head and pumped flow) and electric intensity every minute.

Although most of the district is currently irrigated by drip irrigation systems, Fuente Palmera was originally designed for sprinkler irrigation, with higher pressure requirements.

Hourly irrigation water demand patterns

To classify the irrigation demand in homogeneous groups, the non-hierarchical clustering algorithm K-means (Cuesta, 2001) was used. The objective of this algorithm is to minimise variance within clusters and maximise variance between clusters (Jain, 2000). Its main limitation is that the number of clusters has to be fixed a priori.

The K-means algorithm is based on the minimization of a performance index, which is the sum of the squared distances of all the elements within the cluster to the centroid of the cluster. To measure the distance between elements, the Euclidean distance has been used (Rodríguez-Díaz *et al.*, 2008).

Using the recorded flow at the pumping station, one vector was created for every week including the 24 ratios of the hourly average pumped water to daily average pumped water. Following this procedure, a daily water demand pattern was created for every week. Then, the K-means algorithm was applied to these demand patterns, corresponding to the whole irrigation season, and then they were grouped into homogeneous clusters. The analysis was performed for two, three and four clusters.

Performance curves

The information collected at the pumping station was used to energetically characterize the irrigation district. This analysis was carried out in two main steps. The first step was the generation of the frequency distribution of demanded flow for the irrigation season, at 50 L s^{-1} intervals.

The second step was the analysis of the hydraulic performance of the pumps installed at the pumping station. Reliable data on flows, pressures and power recorded at the pumping station were used to establish the pumping station characteristics curves (flow and pressure head; flow and power; flow and performance). Pumping performance (η) was determined as:

$$\eta = \frac{\gamma F H}{W} \quad [1]$$

where γ is the water specific weight (9,800 N m^{-3}), F is the demanded flow rate (m^3 s^{-1}), H is the pressure head at the pumping station (m) and W is the power consumption recorded at the pumping station (W).

Energy efficiency indicators

Energy indicators were selected from those suggested by the IDAE (2008) for conducting energy audits in irrigated areas. In this work indicators have been classified in four groups:

— Descriptor indicators, informing about water use and irrigated areas within the irrigation district.

— Power indicators, analyzing power requirements. They also allow comparison between contracted power and recorded power use. These indicators can be used to assess whether the current energy contract meets the district's power demand, and to provide information to optimize the contract.

— Energy indicators, analyzing energy consumed for pumping and energy costs.

— Efficiency indicators. This is the most important group of indicators. They provide an energy assessment and a district classification. These are the indicators included in this group:

• Energy dependency rate (EDR):

$$EDR = \frac{Total\ volume\ pumped}{Volume\ of\ water\ entering\ the\ system} \quad [2]$$

• Energy change index (ECI):

$$EDR = \frac{\Sigma V_i \cdot H_i}{Volume\ of\ water\ entering\ the\ system} \quad [3]$$

where V_i and H_i are the volume and pressure head supplied by pumping. Thus, ECI represents the average pressure head.

• Pumping energy efficiency (PEE):

$$PEE_i\ (\%) = \frac{W_s}{W_a} \cdot 100 \quad [4]$$

where W_s is power given to the water flow and W_a is the electrical power consumed, determined as:

$$W_a = \sqrt{3} \cdot V \cdot 1 \cdot \cos\varphi \quad [5]$$

where V is the voltage of each pump (V); I is the intensity (A) and cos φ is the pump power-factor. Ws was obtained from the following equation:

$$W_s = \gamma \cdot F \cdot H_m \quad [6]$$

where γ is the water specific weight (9,800 N m^{-3}); F is the flow rate (m^3 s^{-1}); and H_m is the pressure head supplied by the pumping station (m).

• Energy supply efficiency (ESE):

$$ESE = \frac{|\Delta E|}{ECI}\ If\ \Delta E < 0 \quad [7]$$

This index represents the ratio of the theoretical energy requirements and the energy supply. ΔE is the difference between the initial energy of the water (IE) before being diverted from the water source and the energy required for supplying the water and for operating the irrigation system (ER):

$$ID - ER = \pm \Delta E \quad [8]$$

• Overall energy efficiency (OEE), that takes into account the efficiency of the pumping station and the efficiency in the water supply:

$$OEE = PEE \cdot ESE \quad [9]$$

Energy saving scenarios

In order to evaluate the impact of possible energy saving measures, two scenarios were developed taking into account different management strategies. Then, both scenarios were simulated using the EPANET hydraulic model (Rossman, 2000). The second scenario represent an alternative management strategy, not implying any change or upgrade in the hydraulic infrastructures. Their main characteristics are defined below:

— Scenario 1. It represented current management. The network worked on-demand and the pressure head was fixed to 85 m. The hourly demand patterns, calculated using cluster analysis techniques, were used to establish the hourly base demand.

— Scenario 2. The irrigated area was organised in two independent sectors according to a homogeneous elevation criterion. The first sector included the hydrants under 127 m height, while in the second, hydrants above that elevation were included (Fig. 2). In this scenario the network was managed under semi-arranged demand and each sector could irrigate for 12 h per day only. The pressure head was fixed to 65 m and 85 m for scenarios 1 and 2, respectively. In order to ensure that every farm receives the same amount of water as in scenario 1, despite the reduction in the time allowed for irrigation, the base demand was doubled, assuming a uniform distribution pattern during the irrigation period. Therefore farmers had to apply higher flows in a shorter period of time.

These two scenarios were simulated for three days with different water demand levels, 6^{th} June and 15^{th} July (characterized by medium demand, 542.06 and 942.64 Ls^{-1}, respectively) and 14^{th} August (the peak water demand day, 1,478.40 Ls^{-1}).

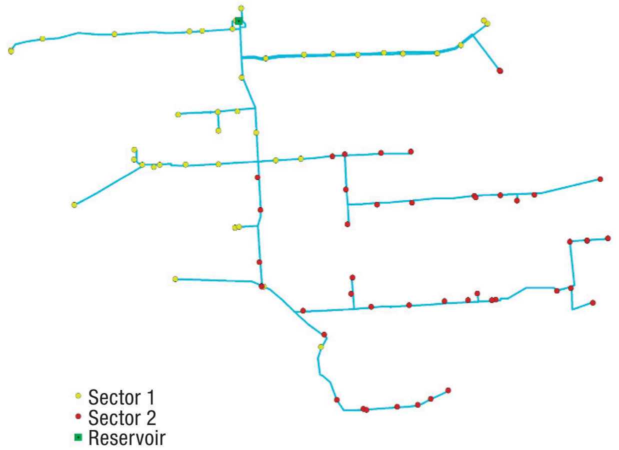

Figure 2. Irrigation network of the Fuente Palmera Irrigation Districts. The two sectors used in scenario 2 are represented with hydrants of different colours.

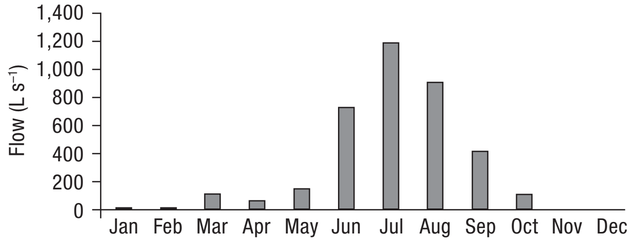

Figure 3. Average monthly irrigation water demand in 2007.

Results

Hourly demand patterns of the irrigated area

The evolution of the average monthly water demand in 2007 is presented in Figure 3. The irrigation season started at the beginning of March and ended in the middle of October. The peak demand period occurred from June to August. Although the month with the largest demand was July, the peak daily irrigation demand was on 14th August (1,478 L s^{-1}). Between November and February farmers did not irrigate.

The weekly demand patterns were used to perform the cluster analysis. The irrigation season took 43 weeks. After repeating the analysis for two, three and four clusters, the best fit (minimizing the variance within clusters) was obtained for two clusters. One of the clusters included 35 weeks, with small variability among hours (cluster 1 in Fig. 4), and the second cluster included the eight remaining weeks, with significant variability between peak and off-peak hours (cluster 2 in Fig. 4). Cluster 2 included the low water demand weeks.

Cluster 1 covered the peak demand period and its standard deviation (0.64) was smaller than in cluster 2 (0.70). Therefore cluster 1 was the most representative irrigation pattern of the irrigation district. In this cluster, water consumption was very homogeneous during the day, with slight increases during the mornings and afternoons (from 18:00), regardless to the energy costs. In cluster 2, consumption was mostly concentrated from 7:00 to 14:00. Thus, most of the water demand occurred when the energy price is maximum.

Energy analysis

Figure 5 presents the frequency distribution of pumped discharge. Results confirmed that low flows were the most common. Actually, 40% of the instant flows were in the range 0-0.05 $m^3 s^{-1}$. However, when a discharge of 0.1 $m^3 s^{-1}$ was exceeded, flow frequencies sharply dropped, always remaining below 3% frequency in each interval.

The hydraulic behavior of a particular pump is specified in its characteristic curves, which relate discharge, pressure head, hydraulic performance and power. These

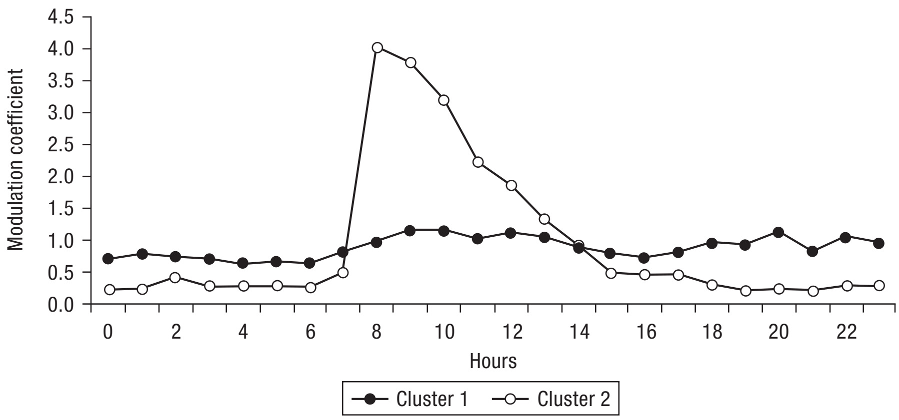

Figure 4. Hourly demand patterns.

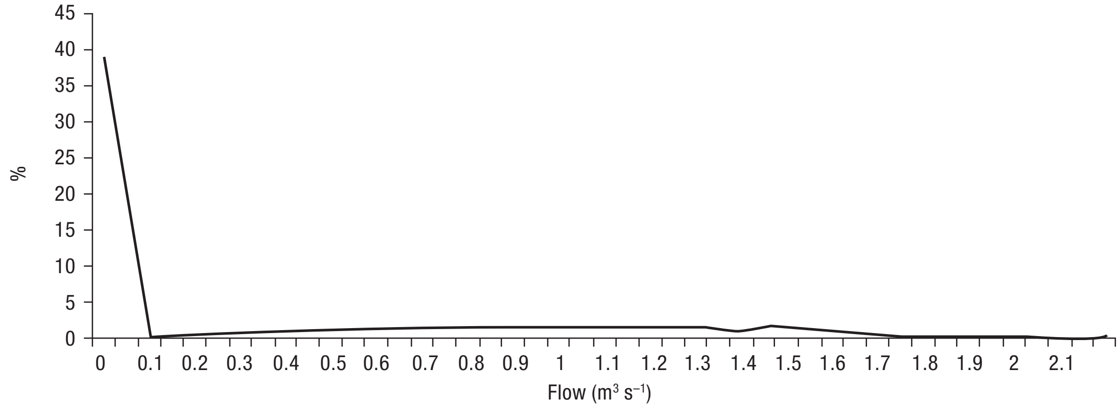

Figure 5. Frequency distribution of pumped discharges in the Fuente Palmera district.

curves were derived from actual data recorded at the pumping station every 15 minutes and are presented in Figure 6 (a, b, c). The comparison of Figure 6c (performance of the pumping station) with Figure 5 (discharge histograph) shows that for the most common flow rates (0-0.1 $m^3 s^{-1}$) the pumping station performance was extremely low (even lower than 25%). Flows above this range can be classified in two groups: the first group was composed of flows from 0.1 to 1 $m^3 s^{-1}$, where performance may exceed 90%; the second group included flows in excess of 1 $m^3 s^{-1}$, for which performance was around 70%.

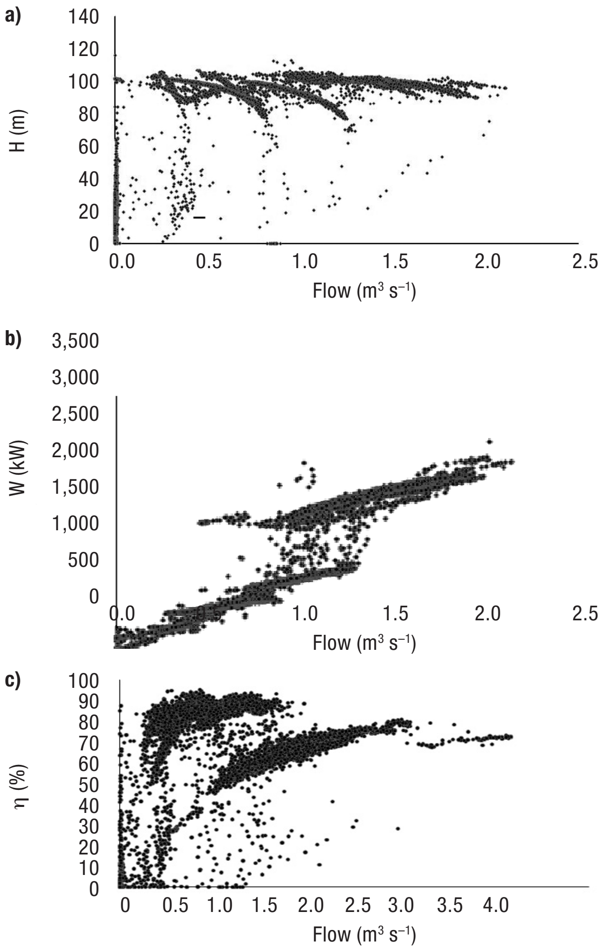

Figure 6. Characteristic curve of the pumping station: a) head as a function of discharge, b) power as a function of discharge, c) pumping station performance as a function of discharge.

Performance indicators

Descriptors (Table 1)

The average applied depth was 1,783 $m^3 ha^{-1}$ and the irrigated area during the studied irrigation season was 5,228 ha. The applied depth was significantly smaller than the irrigation water requirements, which were estimated as 4,760 $m^3 ha^{-1}$. The deficit irrigation is a common practice in this irrigation district and less than half of the total water requirements are applied. Comparing the volume of water diverted for irrigation (measured at the pumping station), and the volume of water supplied to users (measured at the hydrants), the conveyance efficiency was estimated as 96%, which implies adequate maintenance with very low water losses.

Power indicators (Table 1)

Although the average recorded power was 1,989 kW, there was a significant variability among months. The peak power was 5,070 kW. Even during the peak demand season the power performance (ratio of the recorded power and contracted) was 68%. The contracted

Table 1. Descriptors, power performance, energy performance and efficiency indicators of the Fuente Palmera irrigation district

Descriptors	
Irrigable area (ha)	5,612
Irrigated area (ha)	5,228
Volume of water entering the system (m^3)	9,759,313
Volume of irrigation water supplied to users (m^3)	9,318,984
Irrigation water per unit irrigable area (m^3 ha^{-1})	1,660
Irrigation water per unit irrigated area (m^3 ha^{-1})	1,782
Power	
Maximum monthly contracted power (kW)	7,500
Maximum power recorded (kW)	5,070
Maximum power performance (%)	68
Maximum power recorded per unit irrigated area (kW ha^{-1})	0.9
Average monthly contracted power (kW $month^{-1}$)	2,800
Average monthly consumed power (kW $month^{-1}$)	1,989
Average power performance (%)	71
Power factor (%)	95
Energy	
Annual energy consumption (kWh)	7,114,186
Reactive energy consumed (kWarh)	300,382
Energy consumed per unit of irrigated area (kWh ha^{-1})	1,361
Energy consumed per volume of irrigation water that enters the system (kWh m^{-3})	0.73
Energy cost per irrigable area (€ ha^{-1})	93
Energy cost per irrigated area (€ ha^{-1})	87
Energy cost per m3 which enters the system (€ m^{-3})	0.05
Energy cost per m3 delivered to users (€ m^{-3})	0.05
Energy cost to total water costs ratio (%)	28
Efficiency	
EDR: Energy dependency rate (%)	100
ECI: Energy charge index (m)	70
PEE: Pumping energy efficiency (%)	69.5
ESE: Energy supply efficiency (%)	80.8
OEE: Overall energy efficiency (%)	56

power could be reduced, achieving relevant savings in energy tariffs. In the off-peak months both recorded and contracted power were significantly lower, being the ratio for the entire season 71%. The ratio of the peak power consumption and the irrigated area was 0.9 kW ha^{-1}, which is small in comparison with the total installed power (2.2 kW ha^{-1}). Thus the pumping capacity was too big even for the peak demand months.

Energy indicators (Table 1)

In the Fuente Palmera district 0.73 kWh were required to pump every cubic meter of water, implying energy consumption per unit of irrigated area of 1,360 kWh ha^{-1}. The average energy cost was €0.05 m^{-3}. As a consequence, energy represented about 30% of the total Management, Maintenance and Operation (MOM) costs.

Efficiency indicators (Table 1)

Since in the Fuente Palmera district all water is pumped, the EDR was 100%, being the ECI 70 m. The PEE indicator was around 70%, which in the classification proposed by IDAE (2008) is considered as excellent efficiency, included in Category A.

The ESE indicator depends on the network's design and management as it represents the ratio between the minimum energy required by the system for supplying water to all the hydrants and the energy consumed in

Table 2. Summary report of energy indicators determined applying Epanet to the different scenarios[a]

Day	Average demand (L s^{-1})	Average pumping energy efficiency	kWh m^{-3}	Average power (kWh)	Peak power (kW)	€ day^{-1}
Scenario 1						
06-Jun	652	75.02	0.31	718	931	1,162
15-Jul	943	77.74	0.30	1,028	1,498	1,764
14-Aug	1,478	67.07	0.33	1,768	2,274	1,819
Scenario 2						
06-Jun	652	72.41	0.32	1,398	1,886	1,049
15-Jul	943	69.74	0.32	1,583	2,080	1,601
14-Aug	1,478	71.07	0.32	1,490	1,983	1,596

[a] Energy consumption in the first pumping station, from the Guadalquivir river to the reservoir, is not included in this analysis.

the pumping station. In the particular case of Fuente Palmera this indicator was 80.8%.

The OEE takes into account PEE and ESE. In Fuente Palmera OEE is 56%, which is a relatively small value for this indicator. It means that the irrigation district is classified as C (normal efficiency) in the classification proposed by IDAE. Since PEE was classified as excellent, corrective measures should be aimed at improving the ESE indicator.

Energy saving scenarios

The output of the EPANET simulations for the three studied days (6th June, 15th July and 14th August) is summarized in Table 2.

Pumping performance was slightly higher for scenario 1 (where the network operated on-demand, ranging between 67% and 77.74%) than for scenario 2 (where irrigation was organized in two sectors, with an average performance of 71%).

When the average flows presented in Table 2 were analyzed in Figure 6c, on 6th June and 15th July, performance was around 80% (these average flows are on performance curve's maximum). For flows larger than 1 m^3 s^{-1} (as happened on 14th August) performance was less than 70%.

Although the average power was very similar in the on-demand and sectored scenarios, the peak power was significantly reduced when sectoring was introduced. This is because in scenario 2 the water demand pattern was uniform, avoiding peaks in irrigation demand. This reduction in the peak power led the pumping station to work more time under high performance conditions and therefore implied a reduction in the daily energy costs. Actually, in scenario 2, reductions of up to 12% in energy costs could be achieved. The savings in relation to scenario 1 in both, peak power and energy costs, are summarized in Table 3.

Discussion

With the aim of improving irrigation efficiency, modernization of obsolete open channel distribution networks has been a common practice in Spain in the last decades. On-demand irrigation represents a step forward in flexibility for water users and an efficient way to reduce the water demand. On the other hand, it implies a significant increase in energy costs. In the coming years, irrigated agriculture will have to face the challenge of improving efficiency in all the resources involved in agricultural production, not only water. Thus, it is time to reflect on this and assess whether on-demand irrigation represents a clear benefit in terms of global sustainability and on the economic profitability of irrigated agriculture. In this context, energy audits represent an important measure to evaluate energy use in irrigation districts and to detect inefficiencies.

In this work, the energy audits protocol has been applied to Fuente Palmera irrigation district. Analyzing the obtained indicators, the district was globally

Table 3. Peak power and energy cost savings (%) in the scenario 2

Day	Peak power savings	Energy cost savings
06-Jun	–3.45	9.72
15-Jul	11.3	9.27
14-Aug	14.44	12.29

classified in group C (normal) according to the classification provided by IDAE. The OEE was estimated in 56%. These findings are consistent with other works in different Spanish regions, where the average OEE for several irrigation districts take value similar as 67% in irrigation districts in Murcia (Abadía *et al.*, 2007), 41% in Castilla-La Mancha (Córcoles *et al.*, 2008) or 59% in irrigation districts of Navarra (Ederra and Larumbe, 2007).

Introducing sectors in network management (organizing farmers in two shifts) was proposed as an energy saving measure. Additionally, this energy saving measure improves ESE (Rodríguez-Díaz *et al.*, 2009). The viability of this measure has to be analyzed in every case, checking that the on-farm irrigation systems can perform adequately when the irritation time is reduced. However, Carrillo-Cobo *et al.* (2010) reported that in the particular case of Fuente Palmera, even in the peak demand months and taking into account that flows are limited to 1.2 L s^{-1} ha^{-1}, farmers would be able to apply their irrigation water with small probabilities of supply failures, mostly when the local practices (deficit irrigation) are considered.

This management strategy was hydraulically simulated on EPANET, resulting in energy savings of approximately 12%. These energy savings may compensate the increment in energy tariffs. Further energy savings could be achieved by improving the hydraulic structures, such as the pumping station or the network layout and dimensions.

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