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RESEARCH ARTICLE

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Assessing the potential of solar energy in pressurized irrigation networks. The case of Bembézar MI irrigation district (Spain)

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Abstract

The high energy requirements and the rising costs highlight the need to reduce the energy dependence of the irrigation sector. Alternative management strategies have been developed to reduce the energy consumption of the irrigated areas and to improve the efficiency in the water and energy use. In addition, the renewable energy sources are starting to be considered as an alternative to reduce energy costs with smaller environmental impacts. In this work, a new methodology, that combines sectoring as energy saving measure and solar energy, is developed. Thus, it reduces the energy requirements and the dependence on conventional energy resources. This methodology is applied to the irrigation district of *Bembézar Margen Izquierda* (Córdoba, Spain). The results show that organizing the network in two irrigation sectors, annual potential energy savings of 30.8% were achieved. Therefore, this measure reduces the annual energy bill in 30.4% without major investments. Then, a 2.1 MW photovoltaic would supply energy to the sector with higher energy consumption. However, conventional energy would be required (with an annual cost of € 33.6 ha^{-1}) when solar energy is not available or it is not enough to supply the demanded flows. Both measures together would reduce the energy costs in 71.7% and the greenhouse gases emissions in 70.5%. The total investment would be Me 2.8 but with a payback period of 8 years. At present, solar energy is a technically and economically viable alternative, which offers both economic and environmental benefits.

Additional key words: water management; renewable energy; solar PV; greenhouse gas emissions.

Introduction

In the interest of sustainable development and the minimization of climate change impacts, national and international policies are prioritizing the improvement in the use of the natural resources. Water is an essential and limiting resource for private use, industry and agriculture that requires large amounts of energy for

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Abbreviations used: AC (alternating current); BMI (Bembézar Margen Izquierda); DC (direct current); GHG (greenhouse gases); IPS (intelligent power system), IRR (internal rate of return); MPPT (maximum power point tracker); NPV (net present value); OHPM (open hydrant probability matrix); PV (photovoltaic); RIS (annual relative irrigation supply); S1 (Sector 1); S2 (Sector 2); WEBSO (water and energy based sectoring operation). **Glossary**: E [daily energy demanded by the pumping station in the peak demand month (kWh)]; EF [emissions conversion factor (kg CO_2eq kWh^{-1})]; $E_{mjl\ X}$P [energy demand at the pumping station in month (m), management scenario (j) and operating sector (l) (kWh)]; E_T [annual energy consumption in the pumping station (kWh)]; G [global irradiation on the PV array plane for the peak energy demand day (kWh m^{-2}) Z]; G* [reference irradiation [1 kWm^{-2})]; H_j pressure in the most restrictive hydrant in each management scenario (j) (m)]; $H_{jl[}$ [pressure head in each management scenario (j) and operating sector (l) (m)]; H_{max} [maximum theoretical pressure head (m)]; H_{pmjl} [lowest pressure head at the pumping station per month (m), management scenario (j) and operating sector (l) (m)]; IN_{im} [daily irrigation need per hydrant (i) and month (m) [mm)]; *K* (Montecarlo iterations); l_i [distances from the pumping station to hydrant (i) along the distribution network (m)]; l_i^* dimensionless coordinate); l_{ma} [distance to the furthest hydrant (m)]; P [electric power of the PV array (kW)]; p_{imj} [open hydrant probability per hydrant (i), month (m) and management scenario (j); $Power_{mj}$ (power requirements at the pumping station in month (m) and management scenario (j) (kW); q_i [base demand (L $^{--1}$); q_{max} [the network's design flow (L s^{-1} ha^{-1})]; R_{imjl} [random number for every hydrant (i), month (m), management scenario (j) and operating sector (l)]; S_i [irrigation area associated to each hydrant (i) [ha)]; t_{dj} [time available (hour)]; t_{im} [irrigation time in hours per hydrant (i) and month (m) (hour)]; z_i [hydrant elevation (m)]; z_i^* (dimensionless hydrant elevation); z_{ps} [pumping station elevation (m)]; α [excess pressure (m)]; γ [water specific weight (N m^{-3})]; η (pumping system efficiency); η_{pv} (photovoltaic array efficiency under the operation conditions).

its distribution (*e.g.* pumping) as well as to reach the quality requirements of the different users (*e.g.* desalination, purification, etc.). This fact highlights the need to improve efficiency in the water-energy nexus, essential for the economic, social and environmental development of any sector. In recent years, irrigation agriculture has increased energy demands and the high energy tariffs, which follow an upward trend, have created an untenable situation for the sector (Corominas, 2010; Jackson *et al*., 2010). In the Southeast of Spain, Soto-García *et al.* (2013) determined that the energy consumption in the irrigation district and on-farm irrigation systems accounted between 18% and 29% of the total annual energy consumed in the water supply. However, the water supply at basin level (from the water source to the pumping station within the irrigation district) represents the highest energy consumption which ranges, according to water sources, between 0.06 kWh m^{-3} (surface water) and 0.98 kWh m^{-3} (external water transfers).

Several studies have been developed to reduce the energy consumption of the irrigated areas and to improve the efficiency of water and energy. Thus, energy efficiency criteria have been incorporated into the design of networks layout and pumping stations (Lamaddalena & Sagardoy, 2000; Pulido-Calvo *et al*., 2003; Moreno *et al*., 2007, 2009; Daccache *et al*., 2010). Other studies have developed strategies for improving management, reducing the energy requirements of the irrigation networks and therefore reducing energy costs. Measures such as the organization of irrigation turns, critical points control or improvements in the efficiency of the pumping station, can reduce the energy requirements without major investment (Moreno *et al*., 2009, 2010; Rodríguez Díaz *et al*., 2009, 2012; Jiménez-Bello *et al*., 2010; Navarro-Navajas *et al*., 2012; Fernández-García *et al*., 2013).

Simultaneously, in recent years there is an increasing awareness among scientists about the emission of greenhouse gases (GHG) that contribute to the global warming effect. CO_2 represents more than 80% of the total GHG emissions. Thus, many studies have incorporated new environmental criteria, aimed at reducing CO_2 emissions, to the network's management practices. In urban water distribution systems, these measures have been developed with the aim of reducing costs, minimizing emissions in the pumping station (Sahely & Kennedy, 2007; Dandy *et al*., 2008; Wu *et al*., 2010a,b; Ramos *et al*., 2011).

In Spain, electricity is produced mainly from fossil fuels and minerals (66%) (REE, 2011). These are nonrenewable resources which use produce significant environmental impacts. The incorporation of renewable energy in water distribution systems is starting to be considered as a new alternative, especially in urban supply systems, to reduce the negative effects on the environment and enable sustainable development in different productive sectors. For example, turbines for harnessing excess energy when there are large differences of elevation are starting to be installed in water supply systems (Ramos & Mellos, 2007). Other alternative is the installation of hybrid systems that establish the optimal combination of several energy sources such as solar, wind and hydro (Viera & Ramos, 2008, 2009; Moura & Almeida, 2009; Baños *et al*., 2011; Ramos *et al*., 2011). These measures allow reducing energy costs contributing to the sustainable management of water distribution systems.

In the agricultural sector is increasingly common the implementation of renewable energy resources (Vick & Almas, 2011), such as the use of solar energy in the control of greenhouses (Abdel-Ghany & Al-Helal, 2011; Ahmed, 2011) or especially in pumping systems for irrigation (Jafar, 2000; Ramazan-Senol, 2012). However, these energy resources are only being applied in small farms with low power requirements (not exceeding 10 kW).

In this context, the aim of this work was to analyze the potential benefits, both economic and environmental, of the joint application of energy saving measures and renewable energy in one irrigation district with high power requirements.

Material and methods

Study area

The *Bembézar Margen Izquierda* (BMI) irrigation district is located in the Guadalquivir river basin (Córdoba, Southern Spain) (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 540 mm and the average temperature is 17.9°C. Climate data was collected from a nearest weather station (Hornachuelos) using data from the Agroclimatic Information Network of Andalusia. The solar radiation profile for BMI irrigation district in 2009

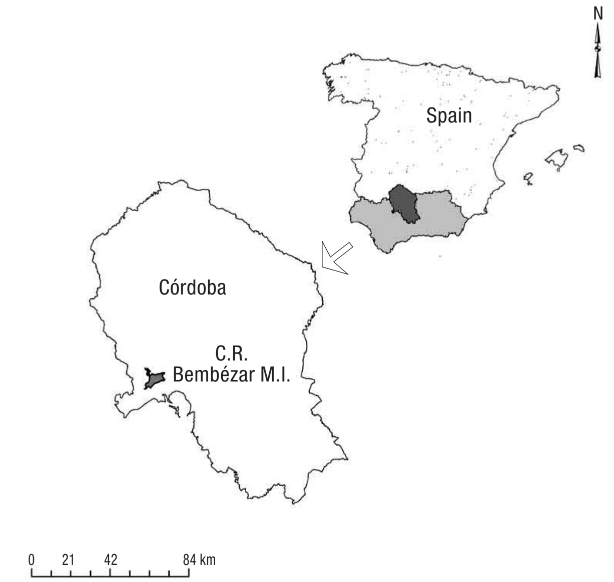

Figure 1. Location of the *Bembézar Margen Izquierda* irrigation district.

(obtained using a pyranometer R01-Skye) is shown in Fig. 2.

The daily average irradiation on the photovoltaic (PV) array is 5.63 kWh m^{-2} day^{-1}. The daily average during from May to August is the 8.34 kWh m^{-2} day^{-1} with a peak value of 8.94 kWh m^{-2} day^{-1}. The irrigation system operates between March and October (daily average irradiation of 6.94 kWh m^{-2} day^{-1}). In perennial and summer crops, which are common in BMI, solar radiation and evapotranspiration have similar time distribution curves, so the peak of solar energy supply coincides with the maximum irrigation requirements.

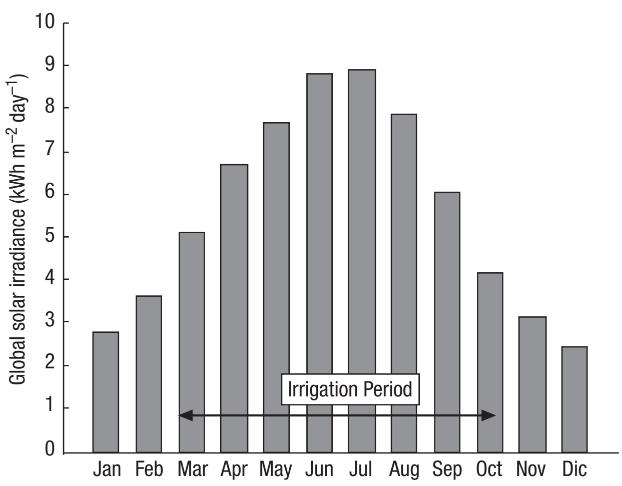

Figure 2. Global solar irradiance at selected Bembézar Margen Izquierda irrigation district. Year 2009.

BMI has an irrigated area of 3,999 ha with a great diversity of crops, being the most representative *Citrus* sp., maize (Zea mays L.), olive (*Olea europaea* L.) and wheat (*Triticum aestivum* L.). The irrigation water is diverted from the Bembézar dam to the pumping station. The pressurized network supplies water to 28 hydrants with a total length of 31.6 km. It was designed to supply 1.2 l s^{-1} ha^{-1} on-demand.

The pumping station has four main pumps of 800 kW and three auxiliary pumps of 315 kW, ensuring a service pressure of 30 m at hydrant level. The network and the pumping stations are monitored by a remote telemetry system which provides pumped flows and pressure data in real-time.

Energy saving scenarios

Four management scenarios were proposed for the analysis of the energy consumption, CO_2 emissions and the energy costs in BMI. The first scenario represented the current operation of the studied irrigation district. The other three presented different management strategies defined to reduce the annual energy dependence and to analyze the potential role of solar energy as alternative energy resources:

— *Scenario 1.* It represented the current management of the pressurized network. The network was organized on-demand so all the hydrants were enabled to irrigated 24 h day^{-1}. The current pressure head, at the pumping station, is fixed to 52 m to ensure a minimum pressure head of 30 m at hydrant level.

— *Scenario 2.* The irrigated area was organized into two independent sectors according to two topological dimensionless coordinates (Carrillo-Cobo *et al*., 2011). The network was managed under semi-arranged demand where farmers were organized in two irrigation turns of 12 h day^{-1}. The required pressure head at the pumping station was different for each sector.

— *Scenario* 3. A PV system was designed to produce the annual energy required by the sector with the lowest energy requirements in scenario 2.Thus, this scenario combines sectoring (energy saving strategy) and the use of renewable energy resources.

— *Scenario 4.* This scenario is similar to scenario 3 but the PV system was designed to supply energy to the sector with the highest energy requirements in scenario 2.

Sectoring operation to reduce energy requirements

Nowadays, most of the pressurized irrigation networks are organized on-demand. To reduce their energy demand, sectoring strategies can be applied. The WEBSO (Water and Energy Based Sectoring Operation) algorithm (Carrillo-Cobo *et al*., 2011) was developed to reduce the monthly energy consumption of on-demand pressurized irrigation networks using a sectoring strategy based on the organization of farmers in irrigation turns according to their energy demand.

The network was organized in homogeneous groups according to the following topological dimensionless coordinates. Then cluster analysis techniques (K-means algorithm) (Mc Queen, 1967) were used to group hydrants into statistically homogeneous clusters.

$$Z_i^* = \frac{z_{ps}}{z_i} \quad [1]$$

$$l_i^* = \frac{l_i}{l_{max}} \quad [2]$$

being z_i^* the dimensionless hydrant elevation, z_{ps} the pumping station elevation and z_i the hydrant elevation. The dimensionless coordinate l_i^* is the relation between the distances from the pumping station to hydrant i along the distribution network (l_i) and the furthest hydrant (l_{max}).

According to the previous sectoring strategy, the WEBSO algorithm was applied to compute the energy requirements (Fig. 3). Initially, the theoretical daily average irrigation needs per month and hydrant (mm) were estimated as described in Allen *et al.* (1998) using the CROPWAT computer model (Clarke, 1998). Then they were transformed into daily irrigation needs, IN_{im} (L ha^{-1} day^{-1}). From this information, the irrigation time in hours per hydrant and month, t_{im}, was calculated as follows:

$$t_{im} = \frac{1}{3600} \times \frac{In_{im}}{q_{max}} \quad [3]$$

where q_{max} is the network's design flow (1.2 L s^{-1} ha^{-1}).

The WEBSO algorithm considered the local irrigation practices adjusting theoretical irrigation needs to the actual water use by the performance indicator Annual Relative Irrigation Supply (RIS). RIS is the ratio of the total annual volume of water diverted or pumped for irrigation and total theoretical irrigation needs required by the crops (Rodríguez Díaz *et al*., 2008) and was calculated per irrigation season. In the study, with high conveyance and application efficiency, the RIS was estimated in 1, after an on-field evaluation using real data from the pumping station

Then, the algorithm assigned an open hydrant probability per month, according Clément (1966):

$$p_{imj} = \frac{t_{im}}{t_{dj}} \quad [4]$$

where t_{dj} is the time available to irrigate according to the management strategy: 24 h when the network operates on demand (scenario 1) and 12 h for the operating sectors (scenarios 2, 3 and 4).

Then, an open hydrant probability matrix, OHPM, with the probabilities per hydrant, month and operating sectors was created. Per each month (m), management scenario (j) and operating sector (l), random patterns of open/close hydrant were analyzed with *k* Montecarlo iterations.

In each iteration, a random number based on the [0, 1] uniform distribution, R_{imjl}, was generated for every hydrant to define if it was open or close. When p_{imjl} was greater or equal to R_{imjl}, the hydrant was assumed to be open and the base demand, q_i, was calculated by:

$$q_i = q_{max} \times S_i \quad [5]$$

where S_i is the irrigation area associated to each hydrant. In the opposite situation, the hydrant was assumed to be closed and its base demand was set to zero.

The hydraulic simulator EPANET (Rossman, 2000) was used to evaluate each network loading condition (open/close hydrant distribution). The hydraulic simulator can be run from the WEBSO code (in visual basic) by its dynamic link library.

The lowest pressure head, H_{pmjl}, needed at the pumping station to supply water to all open hydrant ensuring that the most pressure demanding hydrant receives a minimum pressure of 30 m, was calculated. Initially, the network was simulated for a maximum theoretical pressure head, H_{max}, and the pressure in the most restrictive hydrant (the hydrant with the lowest pressure) was determined (H_j). If this pressure is higher than the required 30 m, the excess pressure (α) is determined (H_j minus the required 30 m). After that, the pressure head at the pumping station was reduced in · m, obtaining H_{pmjl}. The WEBSO algorithm considered this minimum pressure, H_{pmjl}, as the dynamic pressure head defined by Rodriguez Díaz *et al.* (2009).

The original WEBSO algorithm has been modified fixing the pressure head in each sector (H_{jl}). This value, which is the maximum value of all the minimum

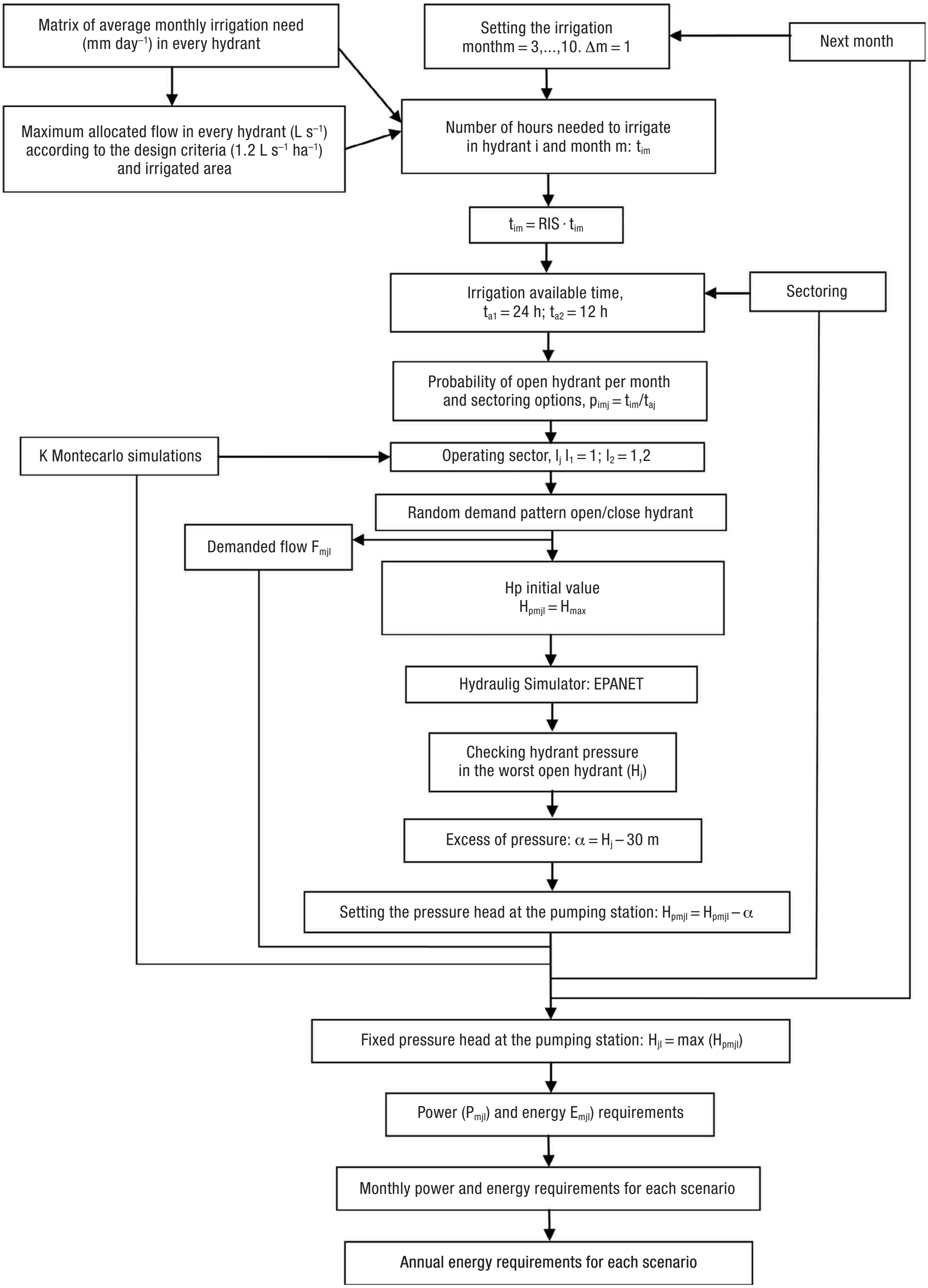

Figure 3. Schematic representation of modified WEBSO algorithm.

pressure head, H_{pmjl}, obtained in each *k* simulation and month simulated for each operating sector, was considered the fixed pressure head for that sector.

Then, the power requirements, $Power_{m,j}$ (kW) and the energy demand (kWh day^{-1}) at the pumping station were calculated according to the following equations:

$$Power_{mjl} = \frac{\gamma \cdot F_{mjl} \cdot H_{jl}}{\eta} \quad [6]$$

$$E_{mjl} = \frac{Power_{mjl}}{1000}$$

where γ is the water specific weight (9,800 N m^{-3}) and η the pumping system efficiency (in this work 0.75).

The process was repeated *k* times for every operating sector and month of the irrigation season (from March to October). The outputs (pumped flow, fixed pressure head for the sector, power and energy) were all recorded. The *k* values of power and energy were averaged to obtain the averaged energy consumption per sector and month. Finally, the annual energy requirements for the four scenarios were obtained.

Solar photovoltaic array setups (solar irrigation systems)

Due to the climatic conditions the solar PV energy technology was selected for this study. The PV power source should be connected to the pump motor (AC) of the pumping station with a DC/AC converter which includes a maximum power point tracker (MPPT) for the proper operation of pumps. These systems usually do not include any battery backup.

As commented above, the irrigation season occurs in months with high solar radiation. However, the smaller production in cloudy days and morning/evening or different seasons may be considered as drawbacks of the system. Therefore, an Intelligent Power System (IPS) should be incorporated. IPS ensures the energy supply to the pumping station even when the solar radiation is insufficient since it allows the connection to the electrical grid. To compute the electric power of the PV system, the following equation was used (International Standard IEC 61724, 1998):

$$P = \frac{\varepsilon}{\frac{G}{G^*} \cdot \eta_{pv}} \quad [7]$$

where P is the electric power of the PV array (kW), E is the daily energy demanded by the pumping station in the peak demand month, G the global irradiation on the PV array plane (kWh m^{-2}) for the peak energy demand day, G^* the reference irradiation (1 kW m^{-2}) and $Ë_{pv}$ the PV array efficiency under the operation conditions (80%). The PV system was dimensioned based on the power requirements obtained from the WEBSO algorithm.

Economic evaluation

In the economic analysis, both the annualized costs of the PV infrastructure and operation costs were considered. The infrastructure cost of the PV system includes the module, structure, electricity works, converter, civil works, control system and processing costs. The operation costs include the electricity consumption in the pumping system and the maintenance of the PV system. The annual energy cost of the corresponding year, for each scenario, was computed by multiplying the daily energy consumption (kWh) by the electricity tariff (€ kWh^{-1}) according to the operation time of the whole network or the sectors. Then, two energy price periods were considered: nocturnal (from 24 h to 8 h) and diurnal (from 9 h to 23 h).

The Internal Rate of Return (IRR) was used as an indicator of the project profitability. IRR is defined as the interest rate at which present value of the cash flows of a project are zero. Higher IRR than the market interest rate means a profitable investment. A discounted cash flow analysis will be performed in order to determine Net Present Value (NPV) of the proposed solar PV array installations. NPV provides an indication of the overall net benefit or loss of the irrigation district when the installation of a solar PV array is considered. Negative NPV indicates that the proposed solar PV systems are not financially viable. The payback period was also used in the economical evaluations. All these rates were calculated for scenarios 3 and 4. A lifetime of 25 years for the PV system and interest rate of 3% was considered.

GHG emissions from water pumping

In Spain, more than 10% of total energy consumption is linked to water (Cabrera, 2011). Agriculture is the sector with the highest water demands (80%), mainly due to the activity of irrigation. In irrigated agriculture, one of the main components of CO_2 emissions is the energy demand for the water supply in pressurized irrigation systems. The GHG emissions in the pumping station were calculated by the following equation:

$$GHG = E_F \cdot EF \quad [8]$$

where E_T is the annual electricity energy consumption in the pumping station (kWh) and EF the emissions conversion factor: 0.264 kg CO_2eq kWh^{-1} (Iberdrola, 2012).

Results

Evaluation of potential energy savings (scenario 1 *vs.* scenarios 2, 3 and 4)

Homogeneous groups of hydrants were created according to the coordinates system defined by l* and z*. Two clusters have been defined using the K-means method in BMI: sector 1 (S1) has 7 hydrants and sector 2 (S2) has 21 hydrants. BMI coordinate z* varied from 0.9 to 1.16, being $z_{ps} = 93$ m and z_i varying between 58 m and 103 m. Only two hydrants were over the pumping station elevation (z* < 1). S1 grouped hydrants with z_i in the range of 84 m and 103 m, while S2 elevations are from 58 m to 79 m. BMI coordinate l* varied from 0 (309 m) to 1 (13,981 m). In consequence, the network was operated in two irrigation turns with 12 hours available for irrigation in each of them.

The WEBSO algorithm was applied to the BMI irrigation district according to the sectors previously established. The network was simulated for the whole irrigation season (March to October) for on-demand irrigation (scenario 1) and two sectors (scenarios 2, 3 and 4).

The *k* number of monthly Montecarlo simulations (8 months) were 2000 for scenario 1 and 4000 for scenarios 2, 3 and 4 (2,000 for each sector). Thus, the total number of simulations was 48,000.

Flow-Pressure head curves were obtained from WEBSO. Fig. 4 shows the Flow-Pressure head curve for scenario 1. In this case, the maximum required pressure head in the pumping station was approximately 48 m (this optimum pressure is 4 m below the current management in the network). Similar curves were obtained for the two sectors of scenarios 2, 3 and 4 (Fig. 5). When the network was operated in sectors the pressure head requirements were significantly reduced. In that case, the maximum pressure head in S1 was 41 m while S2 only needed 34 m. These optimum pressures (48 m, 41 m and 34 m) were used in the energy demand analysis. These reductions in pressure head may lead to lower power and energy requirements and hence to lower GHG emissions.

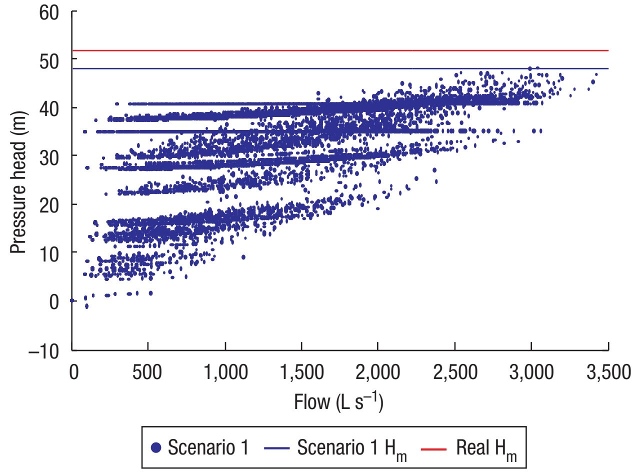

Figure 4. Flow-pressure head curve in scenario 1, optimum pressure head in scenario 1 (scenario 1 H_m) and current pressure head in BMI (real H_m).

The daily energy requirements in every month for on-demand operation (scenario 1) and sectoring operation (scenarios 2, 3 and 4) are shown in Table 1. The average energy savings when the network is operated in sectors were 30.8%, this value is practically constant for all months.

The total annual energy requirements in scenario 1 were 4,319 MWh $year^{-1}$ and in scenarios 2, 3 and 4 were 2,985 MWh $year^{-1}$. When sectoring, S1 demanded 31% (918MWh $year^{-1}$) of the annual energy requirements while S2 demanded 67% (2,067 MWh $year^{-1}$).

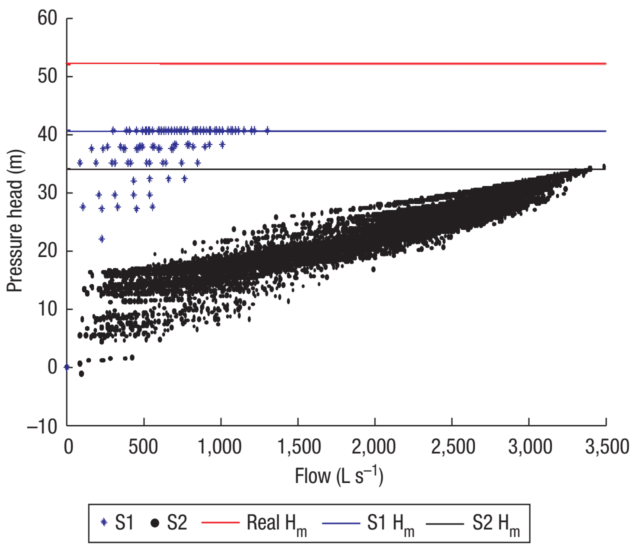

Figure 5. Flow-pressure head curves for two sectors (S1 and S2), optimum pressure head in each sector (S1 H_m and S2 H_m) and current pressure head in BMI (real H_m).

Table 1. Average daily energy requirements (kWh day^{-1}) and potential energy savings (%) for on-demand (scenario 1) and sectoring (scenarios 2, 3 and 4). Year 2009

	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Scenario 1	1,511.4	13,458.1	24,778.3	31,788.8	30,867.5	25,151.8	12,138.8	1,477.7
Scenarios 2, 3 and 4								
Sector 1	339.2	2,894.4	5,324.2	6,751.4	6,555.8	5,244.7	2,585.8	311.1
Sector 2	707.8	6,514.8	11,966.4	15,201.9	14,797.9	11,900.4	5,751.0	726.1
Sector 1 + Sector 2	1,047.0	9,409.21	7,290.6	21,953.3	21,353.7	17,145.1	8,336.8	1,037.2
	(30.7%)	(30.1%)	(30.2%)	(30.9%)	(30.8%)	(31.8%)	(31.3%)	(29.8%)

Optimum PV system (scenario 3 *vs.* scenario 4)

In the previous analysis, the total energy requirements were reduced when the network was operated in two irrigation turns (two sectors). Now, the energy supply options with a PV system are explored.

Scenario 3 evaluates the feasibility of installing a PV system to supply the annual energy requirements in S1 (918 MWh year^{-1}). Thus, S1 would irrigate for 12 hours during the day supplied by solar energy and S2 would irrigate for 12 hours at night, consuming conventional energy resources but with cheaper electrical energy rates. Contrarily, scenario 4 was sized to supply water with solar energy in S2 (2,067 MWh year^{-1}) and S1 would irrigate at night.

The daily energy requirements in the more restrictive month (June) were considered for sizing the PV array. Scenario 3 was sized to provide the daily energy demanded by the S1 (6,751.4 kWh day^{-1}) and scenario 4 for the daily energy demanded by S2 (15,201.9 kWh day^{-1}). The global irradiation in June was 8.8 kWh m^{-2} day^{-1}. In consequence, the PV generator power in the scenario 3 was sized to supply 1 MW and 2.1 MW for scenario 4.

The energy generated by the PV system during an average day in June (peak demand) and March (off-peak demand) in the scenarios 3 and 4 is illustrated in Fig. 6. In months with high energy demand, during sunrises and sunsets the PV array do not produce enough energy to meet the energy requirements as highlighted by the yellow shaded area in Fig. 5. Thus, during these hours, external energy from the electricity supplier must be purchased.

Table 2 shows the balance between the annual energy demand, the PV production and purchased from the electricity supplier. The energy produced by the 1 MW PV system in scenario 3 is used to irrigate S1.

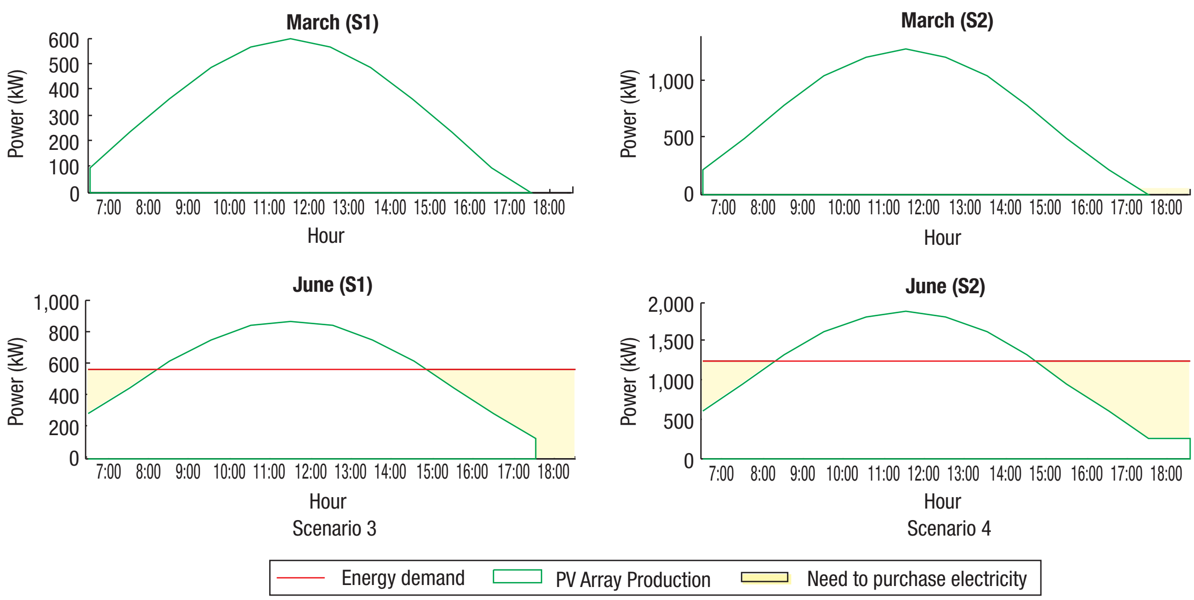

Figure 6. Average hourly photovoltaic array energy production, pumping energy requirements (S1 and S2) and external energy requirements for 1 MW (scenario 3) and 2.1 MW (scenario 4) solar photovoltaic systems.

Table 2. Annual energy balance

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Energy demand (MWh year^{-1})				
Total	4,319	2,985	2,985	2,985
S1	—	918	918	918
S2	—	2,067	2,067	2,067
Photovoltaic array production (MWh)				
Total	—	—	1,648	3,543
Purchased energy (MWh) (%)				
Total	4,319 (100%)	2,985 (100%)	2,215 (74.2%)	1,272 (42.6%)
Sector 1	—	918 (100%)	148 (16%)	918 (100%)
Sector 2	—	2,067 (100%)	2,067 (100%)	354 (17%)

However, during a few hours, additional energy was needed but only 16% of the annual energy requirements. Therefore, the total energy that needs to be purchased from the energy supplier in scenario 3 is 2,215 MWh, 74% of the total energy demand.

The 2.1 MW PV system in scenario 4 produces 83% of the annual energy demanded by S2. The total purchased energy in this scenario 4 is 1,272 MWh (42.6% of the total annual energy demand).

Economic viability

In BMI, the operation costs mainly result from the electricity consumption in the pumping station. The impacts of the implementation of energy saving measures were quantified.

Table 3 shows the energy costs for the 4 scenarios. In scenarios 1 and 2, 100% of the energy requirements had to be purchased. Assuming that night energy (from 0:00 h to 8:00 h) costs € 0.09 kW h^{-1} and that diurnal energy (from 9:00 h to 23:00 h) costs on average € 0.12 kW h^{-1}, scenario 2 reduced the annual energy bill in € 330,668, 30.4% less than in scenario 1 (€ 475,085). This savings can be achieved without any new investment.

Total energy costs in scenario 3 and scenario 4 were € 224,440 and € 134,258, 52.8% and 71.7% respectively smaller than scenario 1. However, scenarios 3 and 4, due to the installation of the PV system, require important investments of M€ 1.3 and 2.8, respectively. The life cycle cost was used to evaluate the financial viability of the system. The unit cost of installed power (W) was € 1.3 W^{-1}. The maintenance and insurance costs were estimated in € 25 W^{-1}.

The results (Table 3) show that scenario 4 is the best option. The NPV of scenario 4 was € 1,276,000 whi-

Table 3. Energy cost analysis

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Energy cost (€)				
Total	475,085.1	330,667.9	224,440.4	134,257.9
Sector 1		82,617.3	17,731.6	91,797.0
Sector 2		248,050.6	206,708.8	42,461.0
Energy cost per area (€ ha^{-1})	118.8	82.7	56.1	33.6
Economic saving (%)	0	30.4	52.8	71.7
Solar photovoltaic power (MW)	—	—	1.0	2.1
Investment (M€)	—	—	1.3	2.8
Financial viability				
Net present value (8%) (€)			288,425	1,276,000
Internal rate of return (%)	—	—	9.1	12.2
Payback (years)			10	8

le in scenario 3 was € 288,425. Both had IRR greater than the interest rate (8%) but the payback value for scenario 4 is 8 years while in scenario 3 is 10 years. Then, in scenario 4, the PV system investment is amortized in the 9th year and from this year to the PV system lifetime (25 years) the economic savings in electricity bills will contribute to increase farmer's profits.

Environmental impacts

The annual GHG emissions from water pumping of each scenario were quantified by the energy provided by the energy supplier. When irrigation turns are adopted, the energy consumption and CO_2 equivalent emissions are reduced. The GHG emissions in scenario 1 is 1140.2 tons CO_2eq (0.285 tons CO_2eq ha^{1}) while in scenario 2 it is only 788.1 tons CO_2eq (0.197 tons CO_2eq ha^{1}); it implies a reduction of 30.9%, similar to the energy reduction achieved after sectoring.

The combination of energy saving measures and the PV system for providing renewable energy offers significant reductions in CO_2 equivalent emissions. Scenario 3 generates GHG emissions of 584.7 tons CO_2eq (0.146 tons CO_2eq ha^{-1}) and scenario 4 generates 335.76 tons CO_2eq (0.084 tons CO_2eq ha^{-1}). Scenario 4 is the best option from both the economic and environmental point of view, reducing the GHG emissions a 70.5% the scenario 1.

Discussion

In Spain, the irrigated areas with pressurized irrigation networks are usually organized on-demand and usually require lots of energy for their operation. Energy activities in irrigation (water pumping) account for 50%-70% of the total GHG emissions of the agricultural sector (Zou *et al.*, 2013). As energy consumption in the pumping stations and GHG emissions are directly linked, the water supply generates significant GHG emissions. Thus, all the measures that reduce the energy demand would contribute to the reduction of the greenhouse effect. From a farmer's perspective, the continued increases in electric tariffs encourage the necessity of adopting energy saving measures that would reduce the total energy costs.

Consequently, in this paper, two strategies for a more sustainable management of pressurized irrigation networks (sectoring and renewable resources) were combined considering economic and environmental criteria. The first strategy to reduce the dependence on fossil resources (sectoring) is based on the organization of the network in irrigation turns. Although sectoring reduces the flexibility, it may lead to energy savings of 30.8% in BMI. These findings are consistent with those found by Rodríguez Díaz *et al.* (2009) and Carrillo Cobo *et al.* (2011) in other irrigation districts but in the same region.

Renewable energy resources have several advantages such as the reduction in dependence on fossil fuel resources and the reduction in GHG emissions to the atmosphere. Previous works have evaluated the technical and economic viability of PV systems in irrigation supply but only for small pumping stations (less than 10 kW). In this work, a PV system for pumping water was designed to supply energy to a high power requirement pumping station. Results showed that, although in cloudy days and morning/evening periods it should be supplemented with energy from conventional resources, it is possible to reduce both energy demand and its cost.

Scenario 4 (PV system of 2.1 MW) was the best of the four studied scenarios. The PV system produces the 83% of the annual energy demanded by S2 and the total purchasing needs from the energy supplier were 1,271,811 kWh (42.6% of the annual energy demand). The total investment was M€ 2.8 but with a payback of 8 years.

Thus, scenario 4 generates 0.084 tons CO_2eq ha^{-1}, reducing the GHG emissions in 70.5% compared to scenario 1 (0.285 tons CO_2eq ha^{-1}). Therefore, renewable energy resources, along with energy saving strategies, can contribute to the sustainability of the irrigation sector in both economic and environmental terms.

However, in this approach the PV system is oversized with 42% of annual excess of energy production. Net metering would solve this problem. Net metering allows the design of the PV system but considering the total annual energy demand, thus the total PV power requirements are reduced. The excesses of electrical energy generated by the PV system are fed back into the energy supplier's grid which is considered like a virtual battery and the annual energy balance (excess of energy supplied by the PV system and energy purchased to the supplier) is performed. Then, net metering system would reduce the power requirements for the PV system and therefore reduce the investment costs.

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