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Standalone direct pumping photovoltaic system or energy storage in batteries for supplying irrigation networks. Cost analysis.

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ABSTRACT

Solar photovoltaic systems have become one of the most popular topics in the water management industry. Moreover, irrigation networks are water- and energy-hungry, and utility managers are likely to adapt water consumption (and consequently energy demand) to the hours in which there is energy availability. In countries such as Spain (with high irradiance values), solar energy is an available green alternative characterised by zero electricity costs and significantly lower environmental impact. In this work, several types of irrigation scheduled programmes (according to different irrigation sectors) that minimise the number of photovoltaic solar panels to be installed are studied; moreover, the effects of the variable costs linked to energy (energy and emissions costs) are presented. Finally, the effect of incorporating batteries for storing energy to protect the system against emergencies, such as unfavourable weather, is proposed. The irrigation hours available to satisfy water demands are limited by sunlight; they are also limited by the condition that the irrigation schedule type has to be rigid (predetermined rotation) and that the pressure at any node has to be above minimum pressure required by standards. A real case study is performed, and the results obtained demonstrate that there is no universal solution; this is because the portfolio of alternatives is based on

investments for purchasing equipment at present and also on future energy savings (revenues). Apart from these two values, there is an economic value (equivalent discontinuous discount rate), which also influences the final results.

KEYWORDS

Cost Analysis, Batteries, Photovoltaic, energy audit, rigid scheduled irrigation

1. INTRODUCTION

The water consumption in 2014 was estimated to be 4,000 billion m^2 (IEA, 2016). Over the next 25 years, water withdrawals are likely to increase by 70% as a consequence of water demands for food production (Alexandratos and Bruinsma, 2012). Moreover, it has been estimated to be feasible to supply adequate food for 50% more population on earth (Pfister et al., 2011).

The International Energy Agency (IEA, 2016) quantified the energy consumed in the water sector as 4% of the global electricity consumption. This energy consumption is projected to be more than two times over the period to 2040. The European Commission (EC) emphasises the Pathways for the transition to a net-zero greenhouse gas emissions economy and strategic priorities (EC, 2018). This document highlights the need to maximise the deployment of renewables and the use of electricity to completely decarbonise Europe's energy supply; furthermore, it underlines Europe’s dependence on oil and gas (which in 2018 represented 55% of the energy demand) and the target for the year 2050 (to decrease to 20% of the total energy demand).

As irrigated agriculture is the world’s largest water consumer (85% of global water consumption; Shiklomanov and Rodda, 2003), the efficient management of pressure irrigation networks represents a challenge for utility managers. In this scenario, wherein the anthropic pressure generates significant consequences in the environment, solar energy emerges as a 'green' alternative because of the reduction in both energy consumption and emissions to the environment. The reductions in the production costs of PV arrays (30–60% in 10 years; Closas and Rap, 2016) in conjunction with the increasing oil prices have endeared this technology to decision-makers and practitioners (Bloomberg, 2016; Nederstigt and Bom, 2014).

Solar water pumping based on photovoltaic (PV) technology in irrigation networks has been used in numerous regions of the world, such as the U.S.A., (Clark and Vick, 2002), India (Pande et al.; 2003) and Turkey (Senol et. al., 2012). There are also certain experiences in the South of Spain (Reca, 2006; Tarjuelo et. al., 2015), a region with high potential because of its high irradiation levels. The key advantage of incorporating PV technology in irrigation is the reduction in grid energy consumption (Chandel et. al., 2015; Hadj Arab et. al., 1999) and its related environmental benefits (Todde et. al., 2019).

With regard to the engineering aspects of these developments, recent works have also solved the problems arising from clouds passing over the generator (Narvarte et al., 2018); in addition, this technique is established to be economically viable. Moreover, the use of a standalone direct pumping PV system without the aid of batteries or other storage device has also been widely studied (Elkholy and Fathy, 2016; Betka and Attali, 2010; Amer and Younes, 2006).

More recently, a tool to minimise the number of PV solar panels required and the energy consumption, in a pressurised irrigation network has been developed (Pardo et al., 2018). It enables utility managers to regulate energy demands by opening and closing hydrants and/or subunits. Thereby, the energy produced by PV panels matches the energy required by crops. However, there are two limitations of this study: first, it can be applied only with the aid of a calibrated hydraulic model (EPAnet, WDNetXL, Infoworks, etc.); secondly, the irrigation schedule must be rigid rotation scheduled irrigation (Repogle and Gordon, 2007), which involves high investments in the automation of hydraulic devices.

In this study, a different set of alternatives for irrigation networks management are assessed, moreover, advancing beyond all the above mentioned references, the additional alternative based on batteries energy storage will also be included. This is a key practical issue because batteries can be an effective option for daily ordinary use, without being limited to emergency situations; energy can be stored at peak hours and released during other periods.

The present energy supply situation, in which pumps are continuously fed from the electricity network, is named as the Zero-Case. All the other feasible alternatives based on solar PV technology for pump driving and/or based on different scheduling methods are compared to it. According to the tool developed, the number of PV panels (Pardo et al., 2018) and the energy savings are calculated in each case. UAEnergy is a freely-available application (https://bit.ly/2FbNqdr), developed for calculating the monthly energy consumption (and the shaft work consumed by pumps) in irrigation networks (Pardo et al., 2013). In order to enable comparison, water consumption and fixed are similar for all the alternatives considered. The variable costs of energy and the environmental costs (carbon credits, tons of CO_2) represent future revenues (to be paid in future). Finally, the alternatives are prioritised based on economic criteria, so that the time period for complete cost-recovery (payback period) is minimised.

The remaining part of this paper is organised as follows: Sections 2.1 and 2.2 describe the infrastructure and hydraulic constraints. Section 2.3 presents the methodology for calculating the number of segments into which the network has to be divided in order to manage the rigid rotation scheduled programme for irrigation. The variable costs of energy are described in section 2.4, and the economic prioritisation is presented in Section 2.5. Section 3 describes the process for calculating the payback periods for the discrete alternatives that utility managers and decision-makers have to encounter while analysing the conversion into a standalone direct pumping photovoltaic irrigation network. A real case study is presented in Section 4; the input data is collected in Section 4.1, and the step-by-step results are presented in Sections 4.2–4.7.

2. MATERIAL AND METHODS

2.1. Upper and lower network flowrate thresholds (infrastructure constraints).

The utility manager operates a water pressurised irrigation network; the network was dimensioned for delivering water for 18 h to exploit the low electricity tariffs at night. When solar irradiance produces energy using the PV arrays for supplying to the direct drive pump, the irrigation time decreases. In local Mediterranean conditions, the number of hours in which photovoltaic energy is produced can be 9 h.

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As the irrigation time is lower, higher flow rates, and consequently higher headlosses owing to friction in the pipes are likely. In this approach, two values appear in the simulation of each water irrigation network. The first is called *lower networks flowrate threshold* ($Q_{low,th}$) and represents the minimum injected flow (for the combinations arising with the opening and closing valves); it does not satisfy the pressure requirements at each node and at each time (for lower flow rates the network always satisfies the pressure standards). Meanwhile, the second is called *upper network flowrate threshold* ($Q_{up,th}$); it is the highest value in which there is a combination that maintains the pressure above the standards (higher flowrates do not satisfy the pressure at any time and at each node). These parameters are of paramount importance while selecting the number of segments (a segment a group of consumption nodes) that can be opened simultaneously.

This flowrate threshold depends on the network layout, diameters, pipe materials, lengths and the flow delivered to plots (which is obtained respect to the irrigated area and the number and type of emitters). The water demand requirements by crops is calculated by considering this flow rate delivered to plots and the irrigation time per hydrant. (or subunit).

All these irrigation pressurised network features can be integrated into a hydraulic simulation software such as EPAnet (Rossman, 2000). Multiple scenarios can be simulated. Moreover, using UAEnergy (an interface developed with Matlab software (Pardo et al., 2019), with which the shaft work in pumps can be calculated (Pardo et al., 2013)), the minimum pressure at each node and at each time of the simulation period and the thresholds are determined and presented here.

2.2. Availability flowrate threshold (hydraulic constraints).

Another constraint (availability flowrate) should also be considered because this represents the maximum flowrate that can be delivered for certain other limitations (i.e. if the network is supplied by groundwater, it could be the maximum flowrate that can be extracted from the aquifer). If the availability flowrate threshold is higher than the injected flow, there is no limitation in our optimisation problem; otherwise, it should be considered in the hydraulic analysis (the minimum value between the available flowrate and network flowrate will be the maximum flow rate injected). This parameter and the two thresholds described above are dependent on the installation (not modifiable by managers).

2.3. Number of segments that can operate simultaneously

As the daily water demand in the network is specified (Q_{inj}) (after performing the hydraulic analysis and considering each consumption nodes demanding water simultaneously), the number of segments (n_{sect}; a natural number between one and n^*) into which the manager divides the irrigation schedule can be selected. By considering a perfect balance while selecting the consumption nodes to be opened/closed, the flowrate injected at each segment is calculated as follows:

$$Q_{sec} = \frac{Q_{inj}}{n_{sect}} \tag{1}$$

This value of flowrate Q_{sec} (Eq. 1) involves a number of segments that may operate simultaneously (n_{sim}) as illustrated in Eq. 2:

$$n_{sim} = \begin{cases} floor\left(\frac{Q_{up,th}}{Q_{sec}}\right) & If\ Q_{sec} < (Q_{low,th}) \\ 1 & If\ (Q_{low,th}) < Q_{sec} < (Q_{up,th}) \\ 0 & If\ Q_{sec} > (Q_{up,th}) \end{cases} \tag{2}$$

In case 2a), as Q_{sec} is lower than the lower threshold, the number of segments that can work simultaneously will be $n_{sim} = floor\left(\frac{Q_{up,th}}{Q_{sec}}\right)$. In case 2b), only one segment may deliver water to crops simultaneously; moreover, in case 2c), as Q_{sec} is larger than the upper threshold, pressure requirements are not satisfied in any of the cases, and n_{sect} should be increased.

The methodology for calculating the number of PV panels (Pardo et al., 2018) revealed that an irrigation schedule is more energy efficient (fewer PV arrays are required) when higher injected flowrates (higher values of $n_{sim} \times Q_{sec}$) satisfy the pressure requirements. As commented before, the irrigation time has now been reduced by solar constraints (D_{irr}, generally up to 9 h, Eq. 3); moreover, the total irrigation time (T_{irr}) has also been defined with regard to the crops' water requirements. With several potential values of n_{sect} and n_{sim}, the system has to satisfy the final constraint:

$$D_{irr} \geq T_{irr} * \frac{n_{sim}}{n_{sec}} \qquad (3)$$

If this inequality is not satisfied, the photovoltaic system will not satisfy the requirement, and the problem does not have any solution. For example, being an irrigation network with 9 h of irrigation time, the number of segments is three, one out of which may operate simultaneously; the total irrigation time will be $T_{irr} \leq 3$ h in order to feed the direct drive pump with energy produced by the PV systems.

2.4. Variable costs linked to energy

In order to compare the benefits of converting the irrigation pressurised network into a standalone direct pumping photovoltaic system, the water consumption (environmental costs of water, social costs, etc) and fixed costs (the utility's structure, asset amortisation, etc.) of water should be equal. According to the cost structure (Cabrera et al., 2013), the variable cost of water is likely to depend on the resource, energy and effective life of the infrastructure; only the second term is relevant in this approach. This refers to the variable energy cost of operation and maintenance (energy cost linked to pumping, treatment and transport; it is proportional to the volume of water treated). This energy cost represents the consumption of grid electricity prior to the implementation of the photovoltaic irrigation system. The environmental costs of greenhouse gas emissions (carbon credits; tons of CO_2) are also calculated.

2.5. Economic prioritisation of the alternatives

As the utility manager is considering the alternative of implementing a standalone direct pumping photovoltaic system, ceratin equipments is to be purchased at the present time: the cost of PV panels, electrical devices, removal of shrubs from the ground, health and safety at work during the installation of the new panels and solid waste management. Meanwhile, the economic savings from reduced energy consumption will be periodically obtained (a cumulative cost to be paid monthly).

In order to enable comparison, all the costs should be expressed in monetary units at the present time using the equivalent continuous discount rate, *r* (Kleiner and Rajani, 2001; Shamir and Howard, 1979). *r* represents the return that could be earned per unit of time on an investment with similar risk.

With these investments and future revenues, the objective function to maximise from the present time (t_p) to the time *t* can be expressed as the net present value (NPV) (Eq. 4):

$$NPV = \left[-I_0 + \int_{tp}^{t} \left(C_{EN} + \left(C_{ENV} * E_p\right)\right) . e^{-rt} dt\right] = \left[-I_0 + \int_{tp}^{t} S_i . e^{-rt} dt\right] \quad (4)$$

where I_0 is the investment performed in year zero, and S_i are the monthly economic savings it can be calculated with the energy costs (C_{EN}) and environmental cost (C_{ENV}) which is proportional to the energy consumed by the pump (E_P)). Equating the derivative of Eq. 4 to zero, the payback period of the investment (Eq. 5) is calculated as

$$T_i = \frac{-1}{r} . \ln\left(1 - \frac{r . I_0}{S_i}\right) \quad (5)$$

where T_i (years) is the payback period; it is to be minimised as lower values involve higher energy savings, and thus higher revenues, per monetary unit invested to buy equipment (PV panels). This value represents the parameter to be minimised when prioritising the alternatives in this optimisation problem.

Finally, if an alternative considers certain other investments in certain other years (as will be required in the numerical example), I_0 should be modified considering these options.

3. OPTIMISATION PROBLEM

The process to select the best alternative is described in this section and in Figure 1. The input data required to execute the model and the calculation process are described here (Sections 3.1 and 3.2, respectively). The parameter to be minimised is the payback period T_i (years) (Eq. 5), a value that considers the future revenues obtained by performing the present investment.

3.1. Input data

3.2. Calculation Process

Step 1: The first stage in the calculation is focused on calculating the upper and lower network flowrate thresholds (infrastructure constraints). This step involves the model's executing using UAEnergy and a software such as Matlab.

Step 2: The availability flowrate should be assessed. If this parameter is higher than the upper threshold, the process may continue to the next step; otherwise, this upper threshold should be equal to the availability flowrate.

Step 3: In order to select potential alternatives for the optimisation, the number of segments and how many of them may operate simultaneously can be calculated with Eq. 4.

Step 4: The number of PV panels is calculated for each alternative (Pardo et al., 2018). Each alternative involves different values of investments and savings. Moreover, a few alternatives including the use of batteries are also incorporated to the analysis in this step.

Step 5: Finally, the payback period is calculated for the alternatives. The minimum values are selected as the best alternative.

4. Numerical example

To illustrate the proposed methodology, a real case study has been previously presented (Pardo et al., 2018): the branched irrigation network (Albamix network) located in the Mediterranean region of Spain. It supplies water to 167.7 ha wherein different varieties of citrus orchards are cultivated., The general planting pattern is 5 × 4 m per tree. The network is compounded by 131 pipes and 132 nodes,98 of them are consumption nodes supplying water to plots. The total length of the network is 4.05 km. The pipe material is PVC, and the pipe roughness of the aged pipes is 0.02 mm (a common value in water irrigation networks according to Mc Govern, 2011). The minimum service pressure required is $\left(\frac{P}{\gamma}\right)_{threshold} = 25\ \mathrm{m.w.c.}$ The data required to calculate the irradiance curves are illustrated in Pardo et al. (2018). This network was originally designed for 18-h irrigation periods. Therefore, in the Zero-Scenario (current state), irrigation is performed for 18 hours at night, to exploit the low energy prices because the pumps are supplied by electricity grids.

Scenarios 1A, 2A and 3A (Table 1) are defined depending on the number of segments into which the entire irrigation network is divided: five, seven and ten, respectively (n_{sect} = 5, 7 and 10).

In all of these scenarios, irrigation lasts for 9 h (7:30-16:30 h), and direct pumping is supplied with PV energy. Segments have been grouped under the criteria of uniformity of pressure and flow (Table 2) at each consumption node. For each of these three scenarios, an additional battery can be considered. In this case, the three alternative scenarios 1B, 2B and 3B arise. The battery would enable energy storage during peak production hours for use during low radiation hours. The estimated service life of the batteries and PV arrays are five and 25 years, respectively. Monthly water demands in the Albamix network have been obtained by combining the meteorological information and crop evapotranspiration for the Penman–Monteith method, from the past 13 years (2005–2017). Regional guidelines (Castel, 2002) have been followed to calibrate the crop coefficients. The resulting monthly average water requirements vary from 18.58 L/m^2 in January to 116.96 L/m^2 in July. These demands are converted into hours of irrigation per month (T_{irr}) (Table 2). Because of the sunlight in that latitude, the daily irrigation time D_{irr} is 9 h. It is observed that the highest water demands occur in July, the month with the highest values of irradiance and of energy production by PV arrays (Pardo et al., 2018; Duffie and Beckman, 2013).

Finally, the aquifer that supplies water to the network permits steady flow rate values of approximately 200 L/s during 10 h. In contrast to the head losses constraint imposed by the network, the available flow rates will not be an actual constraint in many of the situations analysed.

4.1. Input data for Albamix network

The investment required for installing the PV panels depends on the number of segments in each scenario. In particular, 376736 EUR, 283083 EUR and 284351 EUR are the amounts required for n_{sect} = 5, 7 and 10, respectively. The area of each PV panel in this study is 1.6 m^2. Certain additional information is presented at Table 3.

Here, β is the angle of inclination, in radians, of the photovoltaic panels; I_{sc} is the solar constant (1367 W m^{-2}); I_{STC} is the irradiance under standard conditions (1000 W m^{-2}); d is the cell's performance decay coefficient owing to temperature increase (0.004 °C^{-1}); H is the global irradiance on horizontal surface (kWh m^{-2}); T_{STC} is the cell temperature under standard test conditions (25 °C); T_{avg} is the monthly average temperature (°C); φ is the latitude angle in radians (positive to the North); *n* is the day which better represent monthly irradiation (Duffie and Beckman, 2013), a given value; ρ is the albedo (-); PP is the peak power generated by the

PV modules, in W; η_p is the pump efficiency (-); η_{am} is the asynchronous motor efficiency (-) and η_{fc} is the converter efficiency (-).

The monthly irradiation curves for the Albamix network are identical to those already calculated in Pardo et. al., (2018). In particular, the irradiation curve in July is:

$$E_{av}\left(\frac{W}{m^2}\right) = -1.08 \times 10^{15} \times x^5 + 0.08 \times x^4 - 3.80 \times x^3 + 59.44 \times x^2 - 332.72 \times x + 605.41$$

where x is the hour of the day, in hours.

The integration of this parabola between the 7.5th and 16.5th hours, the time during which solar irradiation can be profitably converted into electricity, results in 1766 W/m^2. Considering the pump, asynchronous motor and converter efficiencies, the net energy transferred to water per PV panel per hour of the day can be calculated as shown in Figure 2. The energy produced per PV panel (whose area is 1.6 m^2) is calculated by integrating this parabola; its value is equal to 1210.5 Wh. The cost of the batteries is 32895 EUR; their nominal capacity is 50000 kWh.

The savings thus obtained are the variable energy costs linked to the water distribution in the Albamix irrigation network at zero-scenario, for the six scenarios analysed. These savings have been calculated considering 3.0 Tariff. In Spain, the electricity tariff is compounded by three elements: the price of the power installed (measured in kW), price of the (active) energy consumed (measured in kVArh) and price of the reactive energy (measured in kWArh). The selected tariff comprises three periods each day: the peak period extends for 4 h (prices are 40.72 EUR/kW, 0.018762 EUR/kWh and 0.062332 EUR/kVAr), plain period extends for 12 h (24.43733 EUR/kW and 0.012575 EUR/kWh and 0.062332 EUR/kVAr) and low period extends for 8 h (16.29 EUR/kW and 0.00467 EUR/kWh and 0 EUR/kVAr). In order to maximise the practicality of the study , a 5% tax (direct electricity tax) is added to the sum of the three previous costs; moreover, 50 EUR/month (for renting the electricity meters) and the final VAT

(21%, the general value in Spain; BOE, 2012) are added for obtaining the operation and management costs.

4.2. Network flowrate threshold

In order to calculate the relationship between the minimum pressure and inlet flow, 20000 simulations are performed. In each of the simulations, several hydrants and subunits are opened simultaneous and randomly. The inlet flow values thus obtained vary from 1.1 to 256.6 L/s (the number of consumption nodes opened ranging from one to 73). The minimum pressure registered for these 20000 simulations range between 6.35 and 42.13 m.w.c. (Figure 3). For the simulation stage, 16181 out of 20000 simulations displayed successful water delivery above pressure conditions, 3815 out of 20000 displayed certain node pressures below the standards and four simulations were discarded because of negative pressures.

The lower network flowrate threshold is 152.5 L/s (the minimum flowrate that may imply a minimum pressure below 25 m.w.c.) and the upper network flowrate threshold is 194.9 L/s (the maximum flowrate for which pressure standards can be satisfied).

4.3. Number of segments for the case study

The maximum daily water demand when all the consumption nodes are opened simultaneously is 424.4 L/s. Although this value would not be specified in practice as it is higher than the upper maximum threshold flowrate, the number of segments estimated by the utility manager implies specified values of inlet flow per sector (Eq. 1; Table 4). The availability flowrate (200 L/s) represents a limitation when segmentation into two segments is considered; this is because the network inlet flowrate (Q_{sec} = 212.2 L/s) is higher than the upper maximum flowrate (the minimum pressure would be below the standards (Figure 3)).

The number of segments (n_{sim}) that may operate simultaneously are calculated by Eq. 2,. Finally, the new scenarios should satisfy the final requirement expressed by Eq. 3; in case the irrigation time is likely to satisfy the requirement, 'YES' is displayed in the fifth column (right column in Table 4). If the number of segments is three, the inlet flow per segment supplied is 141.47 L/s (Eq. 1); this is lower than the network flowrate threshold (Figure 3); moreover, according to Eq. 2, only one segment can be opened simultaneously (Table 4). As aforementioned, the irrigation time (T_{irr}) is 3.33 h = 200 min; the profitable time to convert solar energy into pump shaft work is D_{irr}= 9 h = 540 min. Therefore, for those three segments (Eq. 3), 9.99 h = 600 min should be satisfied to fulfil the requirements, and only 9 h = 540 min would be available. In conclusion, it would not be feasible to use this segmentation in this particular case.

Based on these numbers, the most appropriate number of segments is that in which there is an increase in the number of simultaneous segments supplied. Therefore, five, seven and ten segments are the aforementioned candidates (Table 1).

Figure 4 has been obtained for the 4460 simulations (out of the 20000 simulations performed in the network used for Figure 3); it oscillates between the upper and lower threshold (152.5 and 194.9 L/s.). It is observed that 3988 out of these 4460 combinations satisfy the standards, whereas 472 do not. Therefore, an empirical distribution function has been formulated to obtain the probability of occurrence of an event. This is a step function that jumps up by 1/n at each of the 472 values in which the random simulation does not satisfy the pressure requirements. The result at any specified value of the measured variable is the fraction of observations of that measured variable that are less than or equal to the specified value.

According to the numbers for five segments, presented in Table 1 and Table 4, two can be delivered simultaneously (because each segment delivers 85.4 L/s; this is converted into 85.4

× 2 = 170.8 L/s, with pressures above 25 m.w.c. and 99.78% probability; Figure 4). For seven segments, three can operate simultaneously (3 × 60= 180 L/s; moreover, there can be certain alternatives that can satisfy the pressure requirements with 98.31% probability; Figure 4). Finally, for ten segments, four segments can be opened simultaneously because the least effective combination of these four segments is 171.5 L/s (99.78% probability of satisfying the standards). A segmentation considering nine sectors has not been considered as the probability of not satisfying the pressure requirements (87.13 %) is excessively high for this analysis.

4.4. Calculation of number of PV arrays

The number of PV panels has been calculated for the A and B scenarios (Pardo et. al., 2018); the results are presented in Table 5.

In the B-scenarios, certain energy can be stored at peak hours of the day and released when required for the pumps because a battery is available (Figure 5). For each of them, the subunits are opened and closed to minimise the energy consumption (which involves irrigation in the shortest period of time: 500 min for the 1B and 3B scenarios and 480 min for the 2B scenario). Subsequently, the energy audit is performed resulting in 420.51, 413.35 and 420.65 kWh/day per 1B,2B and 3B scenarios respectively. The number of arrays is obtained as the quotient between the energy required by the crops and the energy produced per PV array (1.21 kWh). Finally, the numbers of PV panels for the scenarios analysed are 348, 342 and 348, respectively (Table 5).

4.5. Economic savings

The monthly irrigation hours (input data) is added to the EPAnet model and the energy consumed in Albamix (shaft work, E_p (kWh); Table 6) is calculated.

Moreover, the actual electric consumption considering that the pumps operate with an efficiency of 0.75 is presented (E_l kWh) in Table 6. The equivalent capital continuous discount rate is considered at $r = 2\%$.

The carbon credits saved depend significantly on the energy sources, ; this is because each energy source emits different amounts of CO_2 per kWh produced. In this approach, 554, 865 and 1432 g/kWh are produced if natural gas, oil and coal are the energy sources. These figures have been retrieved from '*Water to Air Models*', a tool developed by Pacific Institute (Wolff et al., 2004). Certain other sources such as nuclear and hydro/solar/wind involve zero greenhouse gas emissions. With regard to the source of energy, the energy mix in Spain (REE, 2015) is reproduced; i.e. 11.4 % of the total energy is produced by natural gas, 21.5% by coal fired and 10.3% by oil fired (Table 6)**¡Error! No se encuentra el origen de la referencia.**. Finally, the carbon credit price is 5 EUR/CC, as stated by the World Bank in its most recent report (World Bank and Ecofys, 2017).

4.6. Payback period for the three alternatives

A-scenarios are cases where investments to purchase equipment are made only in the present time. Therefore, the investment presented in Table 6 is identical to that previously identified in Table 4. As aforementioned, the lifetime of the PV arrays is assumed to be 25 years.

B-scenarios are cases where certain investments (purchase of batteries) are made in future years (the batteries' lifetime is assumed to be five years, and the investments are performed in years zero, five, 10, 15 and 20). I_0 and I_{bat} being values already presented (Table 5), the investment (in EUR) from the present time (t_p) should be (numerical values in Table 6)

$$I_0{}^* = I_0 + I_{bat} + I_{bat}.e^{-5r} + I_{bat}.e^{-10r} + I_{bat}.e^{-15r} + I_{bat}.e^{-20r}$$

The annual savings (the energy consumption by the pumps; in Table 6: C_{EN} = 17307 EUR and C_{ENV} = 596 EUR) are obtained for the scenarios analysed. Finally, the net present value (NPV, Eq. 4) and payback period (Eq. 5) are calculated either for the supply costs (considering only the energy consumption savings) or for the entire economic costs (also considering the environmental costs). The results are depicted in Table 7.

4.7. Influence of equivalent continuous discount rate

A sensitive parameter to be considered is the equivalent continuous discount rate. This parameter represents each cash inflow/outflow that is discounted to its present value. This value depends on the national banks in each country (2.06% in USA; -1.1% in UK; 1.48% Australia, FAO, 2017); moreover, it is a value that is not modifiable by water utility managers. Its influence is illustrated in Table 8.

As can be demonstrated, the 2A-scenario is always the best alternative; however, its results are highly influenced by this term. Low values of the equivalent discount rate involve lower payback periods; to summarise, it is recommended that profits be re-invested to purchase new equipment as the future savings will be marginally discounted, and the investment is returned in a shorter period of time. On the contrary, a high discount rate applied to cash flows occurring further along the time span may be used to reflect long-term debt. This 2A-scenario is ranged from 16.26 to 26.55 years, which is a high variation. As the life cycle of a PV array is considered to be 25 years, it can be assumed to be an economically feasible opportunity for utility managers.

5. CONCLUSIONS

This work demonstrates that converting direct drive pumping systems supplied by electricity grids into a standalone direct pumping photovoltaic system without considering the effect of the type of segments described in the rigid rotation predetermined scheduled selected for this operation can yield significant savings not fully exploited. Certain other parameters such as the upper, lower and availability flowrate thresholds are described. These three terms are infrastructure constraints (the irrigation network was dimensioned for 18-h irrigation) and hydraulic constraints (water withdrawal from aquifers involves numerous limitations, including technical and political limitations). Owing to these constraints, the energy demanded by crops (as a result of the most efficient combination of hydrants opened and closed) does not match the energy produced by PV panels. A cost analysis aimed at evaluating different alternatives is proposed considering all the costs (current costs and future revenues) expressed in monetary units at the present time (with the use of the equivalent continuous discount rate, *r*). This cost analysis returns the best alternative as the one with the lowest payback period. With this structure, the effect of the variable costs linked to energy (energy and emissions costs) and the effect of considering batteries for energy storage to protect the system against emergency situations such as unfavourable weather has been determined. Between these two effects, the first is expected; when the environmental costs with regard to emissions are considered, these three alternatives are more competitive in these irrigation systems. The segmentation that enables the delivery of a higher flowrate while maintaining the pressure requirements become the most economical alternative (With these numbers, the 1A-scenario–seven segments (Table 1), which permits the parallel operation of the three segments, represent the best alternative).

The second (considering batteries) reveals that the short lifetime of the available batteries indicate that the payback period is higher than those obtained without storage of electricity. As the payback period of several alternatives (five out of six) are lower than the PV array lifetime, these alternatives are economically feasible (although in this case study, the 2A-scenario is preferable over others). Moreover, these five alternatives present a scenario with pumps supplied from in situ generated electricity, rather than from electricity grids; this can be an alternative to prevent overload in electricity grids and to obtain electricity in isolated areas.

The key advantage of incorporating PV technology in irrigation is directly linked to their environmental benefits: saving energy saves emissions as well. Although the economic price of carbon credits does not represent large values, these environmental costs are taxes that can effectively minimise the impact of carbon emissions on the environment; thereby, the simulation becomes more realistic. Moreover, this project is completely framed in a future scenario in which these utilities have followed the pathways for the transition to net-zero energy consumption and greenhouse gas emissions.

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