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Evaluation of the design and performance of a micro hydropower plant in a pressurised irrigation network: Real world application at farm-level in Southern Spain

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ABSTRACT

Agriculture is one of the most energy intensive activities within the European Union. The common absence of electric infrastructure in these rural settings has led to the need for in situ generation in many cases. The existing excess pressures in large pressurised irrigation networks makes the generation of micro hydropower here a possible alternative renewable energy source. Pump-as-turbines have been proposed as a cost-effective technology for such purposes, taking advantage of the excess pressure in pipe networks to produce energy. This paper presents a methodology for the design of a plant for micro hydropower generation in an agricultural farm and outlines the predicted benefits of the installation. These predicted benefits were also compared with the measured performance of the plant for the 2019 irrigation season. The main aim of the plant was to replace a diesel generator that supplied energy to the farm. The excess pressure found in the pipe network varied between 0m and almost 60m. The nominal power of the pump-as-turbine was selected to supply the maximum energy requirements of the farm. The predicted operation time of the plant was estimated at up to 3199 h concentrated between April and September. An annual savings of approximately €2950 and 11 t eCO_2 were also estimated. The measured results showed an actual operation time of 2443 h between May and September, as in April the monitoring system was not operational. For this operation time, the savings were €2258 and 8.4 t eCO_2. Considering the April theoretical irrigation time obtained, the savings raised up to approximately €2434 and 9.1 $teCO_2$. The return on investment of the installation was computed to be recovered in less than ten years.

1. Introduction

Agriculture is one of the largest energy consumers in the European Union (EU), accounting for around 2.2% of the total energy consumed in 2016 [1]. In the case of Spain, agriculture was reported to consume 3% of the total energy in 2016, an increase of 43% since 1990 [2]. It is also responsible for significant greenhouse gases (GHG) emissions and climate change contributions. Furthermore, the United Nations forecasted a worldwide population over 9 billion people by 2050, which would dramatically increase the food demand by up to 60% of current levels. This would also affect the associated water and energy demands considering the well-known water-food-energy nexus [3,4].

Agriculture is the largest water consumer worldwide, averaging 70% consumption of the whole water resources and reaching values close to 95% in some developing countries [5]. Thus, more water efficient techniques have been studied and developed during the last decades. Traditional irrigation methods (open surface channels and ditches) have been replaced by pressurised irrigation techniques, such as sprinkler or localized irrigation, which encompassed 14% of the total irrigated area globally in 2014 [6]. This percentage varied depending on the country analysed, reaching values of 50% of the irrigated area in the US, while decreasing in other regions such as India or China. However, this trend is

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changing, since China and India were the countries where localized irrigation gained the most weight in the last two decades, expanding by 88 fold and 111 fold respectively [7]. In Mediterranean regions, the area represented by pressurised irrigation was approximately 60% in 2013, reaching 100% in some countries [8]. Looking to the global perspective, the expansion of drip irrigation kept the same trend, where the drip irrigated surface passed from around hundred hectares to around 10.3 million from 1974 to 2012 [7,9].

These new irrigation methods resulted in an improvement in water efficiency, while increasing the energy dependency. Important water savings were achieved (21%) against increased the energy consumption (657%) in Spain from 1950 to 2007 [10]. Several investigations studied the increase in energy consumption after this replacement process was completed [10–14]. Various solutions have been proposed to improve the energy efficiency of the sector. These were related to either the operational management of the networks, optimisation of the pump stations, optimisation techniques, or the use of renewable energies [15–30]. These studies were focused on the improvement of the energy efficiency in irrigation pipe network distribution systems, attaining energy savings of around 30% in several cases or even the total avoidance of fossil fuel sources for the energy supply. However, there are other locations within irrigation systems as a whole where energy could be saved, such as at farm level. In many cases, the required energy at farm level is produced in situ, using diesel generators to feed the different devices required during irrigation due to the lack of electric grid connections in rural areas. These cases increase the energy dependency of the activity while also increasing the air pollution and climate change contributions.

Renewable energies could be a viable alternative to replace farm-level diesel generators, reducing CO_2 emissions and local air pollution, whilst bringing electricity to remote places with no grid connection. The issue of energy supply in remote places is a universal sustainability challenge for the agricultural sector, and micro hydropower (MHP) could be applied to supply this local farm-level energy demands sustainably. The excess pressure at hydrant- or farm-level in some cases would make the generation of MHP while irrigating and its consumption on site, possible. The total replacement of diesel generation would lead to significant environmental savings, taking advantage of existing hydraulic resources to supply the energy demanded. Moreover, using pump as turbines (PATs) would make MHP an even more attractive solution. Some authors referred to cost-effectiveness as an advantage of PAT technology when compared to traditional hydraulic turbines for small power output schemes [31–33]. Previous investigations studied the theoretical or experimental performance of PATs installed in labs or under actual operation conditions [34]. However, no research was made of actual PAT pilot plants installed and operating in the real-world over an extended period in irrigation network settings.

One of the greatest challenges that researchers have faced in recent years was to predict PAT performance. This is required to foresee the energy recovery potential based on a flow variability and is core to feasibility assessment before the construction of a plant. The lack of actual PAT performance information has led to different approaches and methods to face this challenge. Among other methods, affinity laws, one-dimensional numerical models, definition of quadratic equations, application of the rotor-voluta matching principle, computational fluid dynamics (CFD), or artificial neural networks (ANNs) have been proposed [35–41].

This paper presents new knowledge for the design and feasibility study phase prior to the construction of an MHP plant at irrigation farm level. The paper presents new knowledge on MHP operation in irrigation networks, informed by the first data on actual performance of a PAT plant built in a pressurised irrigation network and installed at farm level. A PAT was designed to replace a diesel generator and to feed the local electrical devices used during irrigation. The plant was designed to take advantage of a small head from the existing excess pressure in the network and a small amount of flow from the farmer's total demand. The considerations taken into account during the design were focused on ensuring no effect on the farmer's activity while guaranteeing the energy supply. The assessment of the potential economic and environmental benefits were first carried out, estimating the farm irrigation time and the plant operation length. A study of the return on investment was made, predicting the payback period of the plant. Both, design benefits and predicted investment return were then contrasted with the actual performance results measured during the 2019 irrigation season. The actual performance of the plant was recorded using a remote monitoring system implemented at the plant, which allowed the analysis of the plant working under actual conditions. The novelty of the work resides on being the first research conducted on the actual operation, design and performance of a pump-as-turbine installation in a real working water network. Lastly, an analysis of two PAT regulation schemes (hydraulic and electric), and the global efficiency of the plant were carried out. The results obtained in this research could lead to a more efficient plant designs and a better understanding of PAT performance working under actual conditions, thus improving the plant power and global efficiency, and sustainability of energy sources applied to the agriculture sector.

2. Materials and methods

2.1. Study area

A pilot PAT power plant was designed, and subsequently constructed at a farm located within the left bank of the Genil river irrigation district (GMI), in Southern Spain. The total area irrigated in this district was approximately 6400 ha with a predominance of citrus and almond crops, although other crop types could also be found, including walnuts and olive trees. The hydraulic infrastructure is composed of a pressurised branched network with pipe diameters that varied between 75 mm and 1200 mm, supplying water to a set of 88 hydrants distributed around the district. The network is fed by two sets of water reservoirs and decanting pools. The service pressure or minimum pressure required at hydrant level was 35m. The network was designed to supply 1.2 $l\ s^{-1}\ ha^{-1}$ on-demand (24 h per day) under the hypothesis of 100% simultaneity (i.e. all hydrants simultaneously open). The aforementioned farm was fed by a single hydrant, irrigating a surface of about 170 ha distributed in three plots, with walnut as the sole crop. A main 400 mm diameter steel pipe formed the water distribution system feeding the irrigation infrastructure within the farm. Three smaller distribution pipes were also present and these had a diameter of 200 mm distributing water around the plots. Three pressure reducing valves (PRVs) were installed in these distribution pipes, as drip irrigation was practised at the farm and low pressures were required in the inlet of the drippers. Finally, the drippers were distributed along the farm, providing the required water to the crops. A location map and the layout of the irrigation district can be seen in Fig. 1, as well as the farm, highlighted in dashed green.

The farm relied on a 6kVA diesel generator for energy consumption due to its location, isolated from the grid. Energy demands included two fertigation pumps, 78 electro-valves for a filtering system, and an air compressor for maintenance operations. The maximum local energy requirements, considering all of these devices requiring working at the same, was 3.6 kW.

The mean annual rainfall and evapotranspiration over the last ten years (2009–2018) amounted to 641.8 mm and 1328.6 mm

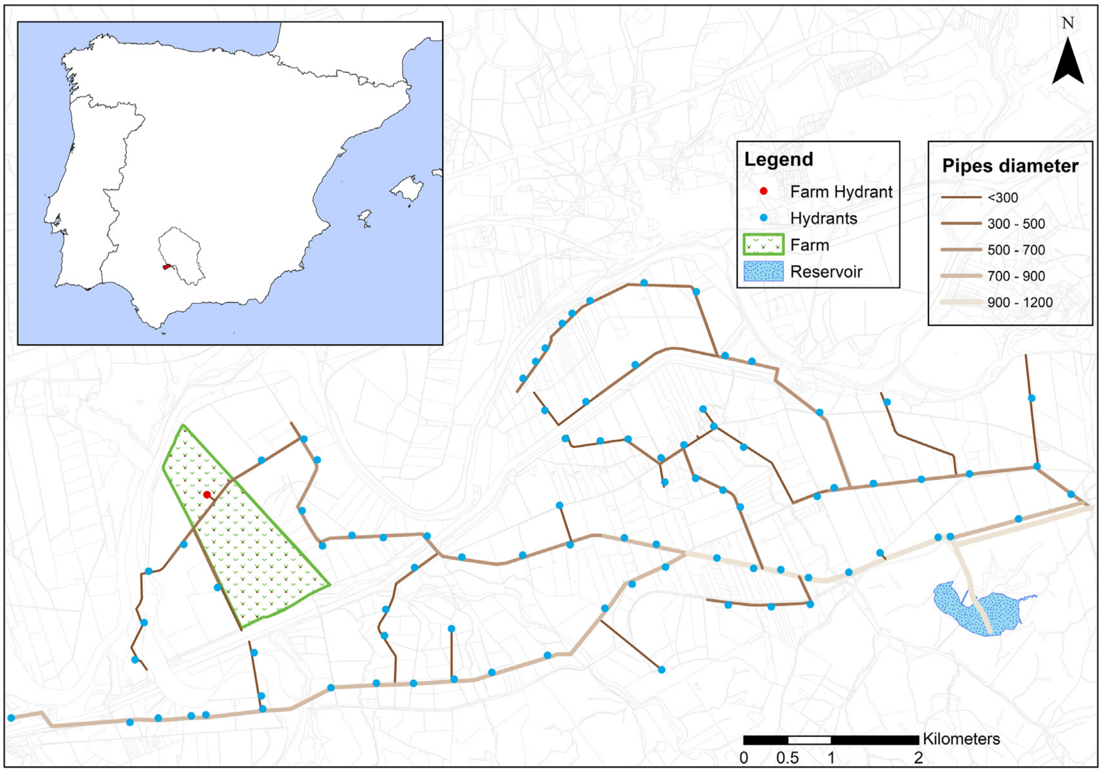


Fig. 1. Location and layout of the network and farm where the plant was constructed (Genil river irrigation district, Southern Spain).

respectively.

2.2. Hydraulic modelling and flow and head predictions

An EPANET hydraulic model of the whole network shown in Fig. 1 was developed [42]. The model enabled the analysis of the existing working conditions in the farm along the entire irrigation season. Modelling was conducted as described in detail in Crespo-Chacon et al. [20]. Obtaining accurate flow and head distributions for the network was important since the operation of PATs are sensitive to fluctuations in flow and head. Inaccurate flow predictions could result in significantly underperforming PATs. Furthermore, measurements of flow and head in irrigation networks are not commonly available and were not available at this network.

For the different flow values at this location, the three plots irrigated by the hydrant were included individually in the hydraulic model, taking into account the areas irrigated and the base demand of each of them. The flow and head distributions were predicted for the issue hydrant using the methodology developed and validated by Crespo Chacon et al. [20,21]. This methodology combined combinatorial analysis and statistical assessment, considering all possible combinations of open/closed hydrants in the irrigation district (upstream of the farm). Then, the flow values domain was defined and the occurrence probability, and thus occurrence time for the specified irrigation season for every possible flow obtained applying the Bernoulli Experiment. The Bernoulli Experiment consisted of repeated and independent trials with two possible outcomes, success or failure. Related to its application into the irrigation district, each hydrant had a monthly probability to be open, which depended on the irrigation requirements needed by the crops. Each trial involved the generation of random values ranging [0–1], which were compared to the probability of each hydrant to be open. The result of a trial was considered as success, and hence the hydrant open, when the random value generated was lower than the probability of the hydrant to be open and vice versa. The number of trials to be run proposed in Ref. [20] was at least twice the number of combinations of open/closed hydrants, thus better characterising the condition of the network. A binomial distribution is obtained from this experiment, which characterised the flow occurrence probability along the irrigation season. With both distributions defined, the method applied a simplified version of the variable operating strategy proposed by Carravetta et al. [43,44].

The Bernoulli Experiment was run in the hydraulic model of the network integrating the EPANET engine into Python (v. 2.7.15) through EPANET's programmer toolkit. Once the Bernoulli Experiment was run, the flow and head distributions were obtained, thus enabling the analysis of the flow and head conditions during the entire irrigation season. This allowed the variation in excess pressure at the farm to be predicted. The occurrence probability for each combination of flow and head was calculated using the mass probability function (see Equation (1)). The cumulative probability function was then obtained and the exceedance probability for every flow and head was estimated.

$$p(X_i) = \frac{n_i}{N} \tag{1}$$

Where X refers to each of the variables (flow and head); n is the number of times that each value was obtained; N is the number of simulations runs; i refers to each of the values of the domains of the variables.

The available flow and head fluctuations at the system makes the installation of a regulation system to control the working conditions of the PAT necessary. This regulation has been proposed to be done using either hydraulic (e.g. valves) or electric devices (variable speed drives). These two schemes are known as hydraulic regulation (HR) and electric regulation (ER) respectively [44–46]. In this installation, both schemes, HR and ER, were used, thus controlling the operation conditions of the PAT to be close to its BEP. In practice, both control systems are not required and the plant could work using just HR. However, the experimental aim of the pilot plant allowed comparison of both control methods. Therefore, a variable speed drive (VSD) and a pressure reducing valve (PRV) were installed. Both schemes had been previously compared by other authors theoretically, concluding a slightly better performance of the ER against a more economic option in case of HR [45]. Firstly, the PRV was operated completely open, therefore allowing the VSD to regulate the rotational speed on its own, depending on the inlet conditions at the PAT. To test the HR, the PRV was set considering the minimum pressure required at the hydrant and the head of the PAT, thus regulating the PAT inlet conditions, which varied depending on the conditions available at the farm, and ensuring the minimum value needed by the farmer respectively. Only operating HR together with the VSD was conducted (combining ER and HR), as the VSD could not be disconnected from the system.

The PAT was proposed to be installed in a 150 mm diameter new bypass in parallel to the existing distribution pipes. The installation scheme can be seen in Fig. 2.

2.3. Design approach and performance prediction

The energy requirement prior to the plant construction was supplied by the diesel generator previously mentioned. The main aim of the PAT was to replace this completely, therefore avoiding the use of fossil fuelled generation. The employment of a PAT together with an energy storage system would allow the full replacement of the diesel generator. This system must be able to supply the required energy even when the farmer was not irrigating (and therefore no flow was occurring at the turbine). Energy storage devices were used to store energy when excess was available and supply it when energy was required outside of irrigation occurring. This solution involved saving 100% of diesel consumption and GHG emissions. The theoretical analysis conducted for the plant design used average climatic conditions from the last 10 years (2009–2018) to account for evapotranspiration and hence water demands. The installation was designed to work at fixed point, as there were not records about the energy demand. The PAT was installed in a bypass scheme, diverting only the flow required to cover the maximum power demand of the farmer (3.6 kW). After analysing the flow and head conditions available at the farm, the possible combination of flows and heads returning the required power were calculated using Equation (2). Furthermore, the variation of the head depending on the flowrate and the performance of the PAT was assessed using Equations (3) and (4), proposed by Barbarelli et al. (2017) and Novara et al. (2017) respectively.

The PAT was selected based on four considerations: i) operability of the farm; ii) maximum energy requirement; iii) best efficiency point (BEP) of the PAT; and iv) economic and environmental benefits.

$$P = QH\gamma\eta \tag{2}$$

$$\frac{H}{H_{BEP}} = 0.922\left(\frac{Q}{Q_{BEP}}\right)^2 - 0.406\left(\frac{Q}{Q_{BEP}}\right) + 0.483 \tag{3}$$

$$\eta = 0.5197\left(\frac{Q}{Q_{BEP}}\right)^3 - 2.3328\left(\frac{Q}{Q_{BEP}}\right)^2 + 3.0931\left(\frac{Q}{Q_{BEP}}\right) - 0.2757 \tag{4}$$

Where P is the power production in kW; Q is the flow running through the turbine in $m^3\ s^{-1}$; H is the head in m; γ is the specific weight of the water in $N\ m^{-3}$; η is the efficiency (%). Q_{BEP} and H_{BEP} refers to the best efficiency point values.

2.3.1. Irrigation operability

One fundamental aspect that the PAT design took into account was the extent to which the operation of the farm would be affected

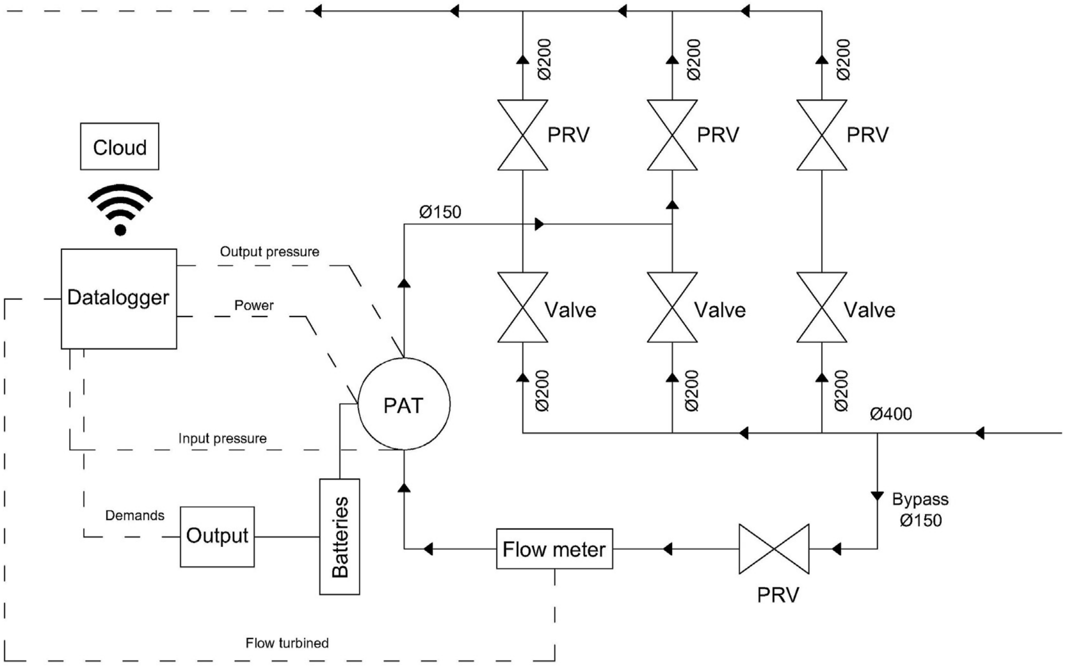


Fig. 2. Plant scheme, including the device connection to the datalogger in dashed.

by the presence of the turbine. The activity of the farmer could not be altered when the PAT was installed, as the primary function of the network (irrigation), must not be affected by hydropower production. There is a minimum pressure value required at hydrant level for the proper functioning of the irrigation infrastructure. Hence, the pressure value after the PAT installation had to be at least equal to this service pressure. In order to ensure no effect on the irrigation network operation, backup energy systems were also required to feed local demands in case of insufficient available pressure for energy production. As the main purpose was the total replacement of the diesel generator and due to the lack of grid, energy storage systems could be used as backup.

2.3.2. Energy requirements

The energy requirements could vary depending on the activity of the farmer and the stage of the irrigation season. Therefore, the nominal power of the installation (3.6 kW) was fixed to always ensure the maximum energy demand. Nevertheless, as the energy requirement could vary, the energy produced could be higher than the energy demanded on a regular basis. Power heatsinks were installed to dissipate the energy not being used by the farmer in those periods where not all the power was required.

2.3.3. BEP selection

Regarding the BEP, the flow demanded and available head at the hydrant suffered significant fluctuations, greater than in other types of water network. Therefore, the occurrence probability of flows and heads were analysed, finally selecting the BEP that ensured the energy supply along the irrigation season or, in case of lack of flow or head, during most of the irrigation season, including those periods of intensive demands, concentrated in July and August.

2.3.4. Economic and environmental savings

The payback period (PP) was an important variable to consider the investment risk in designing the MHP installation within the irrigation sector. These networks only work during concentrated periods from approximately April to October, thus limiting the operation time of the plants and their cost-effectiveness. To carry out the economic analysis, the economic savings generated by the plant and its cost were evaluated. The savings depended directly on the annual volume of diesel saved. The diesel volume consumed per unit time, the cost of diesel per litre and the operation time of the farm were hence required.

The diesel consumption per working hour was obtained from the technical sheet of the generator, fixed at $1.2\ \mathrm{l\ h^{-1}}$. The operation time during the season depended on the BEP of the PAT design and its occurrence probability. This was previously estimated for each flow and head. The seasonal volume consumed was obtained multiplying the unit consumption by the operation time. A mean cost of €0.77 per litre for the 2019 irrigation season was obtained from the records of agricultural diesel prices for that period in Spain [47]. The savings were then estimated multiplying the seasonal diesel volume estimated by the mean cost of the diesel. The cost of the PAT and civil and electric works were estimated using the model proposed by Crespo Chacon et al. [20]. This considered the cost model for electromechanical devices developed by Novara et al. [48] and civil work costs for MHP plants in irrigation networks depending on the nominal power of the PAT. The cost of the backup system and heatsinks were also taken into account.

Another key aspect to be considered was the avoidance of GHG emissions. The environmental benefits would be related to the existing supply system, in the form of emissions saved. Thus, to estimate the emissions, two parameters were required: i) the diesel volume used for the whole season; and ii) the emission factor for diesel generators. The Spanish emission factor for fixed diesel generation equipment was used ($2.868\ \mathrm{kg\ eCO_2\ l^{-1}}$for diesel type C, for 2018 [49]). The amount of emissions savings was then calculated multiplying the seasonal volume of diesel employed by the emission factor.

The equations for the annual revenues (AR), emission savings (ES) and PP are described in Equations (5)–(7).

$$AR = Operational\ time\ (h\,/\,yr) * Diesel\ consumption \left(\frac{l}{h}\right) * Diesel\ cost(€) \tag{5}$$

$$ES = Operational\ time\ (h) * Diesel\ consumption \left(\frac{l}{h}\right) * Emission\ Factor \left(\frac{CO_2}{\mathrm{l}}\right) \tag{6}$$

$$PP\ (yr) = \frac{Cost\ (€)}{AR\ (€)} \tag{7}$$

2.4. Installation and performance measurements

The final plant installation was completed following the guidelines given in the previous section but with small differences. The final plant had a 4 kW nominal power output and was composed of a PAT installed in a 150 mm bypass with a set of four batteries connected in series. The PAT installed was a KSB INLINE 080-B pump, whose BEP as a turbine corresponded to $30\ \mathrm{l\ s^{-1}}$ and 20 m.

The theoretical and actual power and BEP of the PAT differed slightly. This was one of the limitations reported in the Crespo-Chacon et al. [20] methodology, where the optimum theoretical PAT recommend by method must be matched with the closet actual PAT available on the market. Other properties of the PAT were an 80 mm diameter inlet and outlet flange and a 174 mm impeller. The nominal speed of the device was 1800 rpm. The generator used was a Eura Drives EVPM model with a four poles permanent magnet motor, and a nominal power of 4 kW. The nominal rotational speed was 1500 rpm. The maximum global efficiency of the plant was 68% (see Table 2). The batteries employed corresponded to the monoblock sealed AGM model MEBA12-220 from the manufacturer ME. These had a voltage of 12V, an Ah capacity of 220 Ah, and a total capacity of 10.56 kWh. The head, power and efficiency curve as per the flow rate can be seen in Fig. 3. The values plotted in the figures can be seen numerically in Table 1. The charge regulator installed to test the ER was a Schneider Electric model Conext MPPT 80,600.

In addition to the PAT, generator and the energy storage system, two solar panels were installed with a total nominal power of 660W. The model used was the Amerisolar AS-6P. The aim of solar panels was to maintain the charge level of the batteries in those periods outside of the irrigation season (October to March). This would avoid the total discharge of the batteries leading to their damage or failure over the long term.

A monitoring system was also installed at the plant in order to record the working conditions and the actual results obtained. The system was based on a GPRS datalogger, which allowed remote access, displayed live data, and stored the data monitored in historical files. The datalogger installed was a Hermes M100 combined with the model M120, from Microcom. The system used a SIM card to send the data to the ZEUS server, a cloud provided by Microcom where the data was stored and displayed.

The devices used for the data monitoring included: a Hidroconta

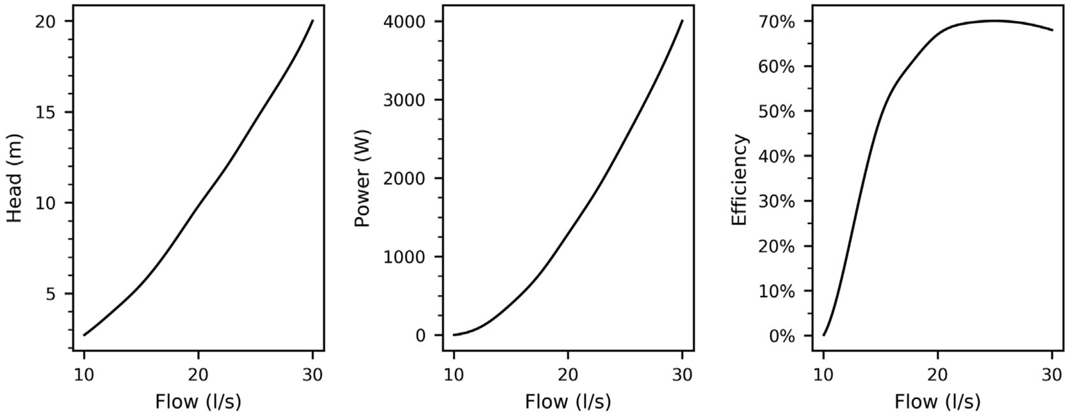


Fig. 3. Head, power generated and global efficiency curves of the installed plant depending on the flow rate.

Table 1
Summary of the PAT performance values.

Flow(l/s)	Head (m)	Global Efficiency (%)	Power (W)
11.7	11.4	0.01	11.8
13.6	13.1	0.14	247.8
16.2	14	0.36	801.6
18.9	14.9	0.48	1333.0
21.5	16	0.57	1936.7
22.9	17.1	0.67	2570.3
25.8	18.5	0.68	3165.7
30	20	0.68	4002.5

ultrasonic flow meter; two pressure gauges recording the inlet and outlet pressure at the turbine (Danfoss model MBS 1700) (see Table 3); the voltage of the batteries was monitored directly in one of the inputs of the datalogger; energy generated by the turbine and consumed by the local irrigation devices were also registered in the datalogger. These variables were registered every 30 s, amounting to a high definition data set, which allowed the quantification of the actual benefits achieved during the irrigation season in 2019 and the plant performance.

3. Results

3.1. Performance prediction

The irrigation period for the farm was estimated to be carried out between April and September. Considering the existence of the three different sectors irrigated by the selected hydrant as individual hydrants, eight combinations of open/closed hydrants were possible. Crespo Chacon et al. [20] stated that the number of monthly simulations should be at least double the possible combinations in order to increase the likelihood of every possible combination to occur. Nonetheless, the minimum pressure found at the hydrant at the farm when all the hydrants in the remainder of the network were open (100% simultaneity) was 32 m. This was a little lower than the required pressure of 35 m. This fact meant that no head could be recovered by the PAT under these conditions. Thus, the amount of combinations of open/closed hydrants for the whole network had to be examined to study the head conditions at the farm hydrant in more detail.

The required number of combinations considering the 88 hydrants in the full distribution network was up to 5.8×10^{23}. However, the number of simulations to be run had to be reduced, since it was not possible to carry out this number of simulations due to limitations of computational resources. Thus, the Bernoulli Experiment was run employing three million simulations, for which the flow and head values were predicted. To inform the design of the PAT, the flow was predicted at the inlet pipe, and the pressure at the main hydrant was also predicted. This data can be seen in Fig. 4a for the whole irrigation season. The minimum pressure predicted at the hydrant was 35 m, which appeared just once out of the three million simulations. This value occurred when around 90% of the farmers in the district were simultaneously irrigating and reflected how for those intensive irrigation periods there was a small probability of not having any excess pressure available. This issue made the inclusion of the energy storage system necessary as backup to ensure the reliability of the energy supply. Although the occurrence probability for those high simultaneity events was predicted to be low, as shown in Fig. 4b, the main aim of the plant was ensuring the energy supply, fully

Table 2
Summary of the main properties of the electro-mechanic equipment installed

Device	Model	Material	Inlet DN	Outlet DN	Efficiency	Rotational speed
PAT	Inline 080-B	Cast-Iron	80 mm	80 mm	79.7%	1800 rpm
Generator	Permanent magnets	Cast-Iron	-	-	91.0%	1500 rpm

Table 3
Summary of the main properties of the monitoring equipment installed

Device	Model	Output signal	Accuracy	Range	Response
Flow meter	Ultrasonic	4-20 mA	> 2%	-	16 ms
Pressure gauge	MBS 1700	4-20 mA	0.50%	0 - 10 bar	4 ms
Data logger	Hermes M100 + M120	4-20 mA	0.1% - 0.5%	6 inputs	-

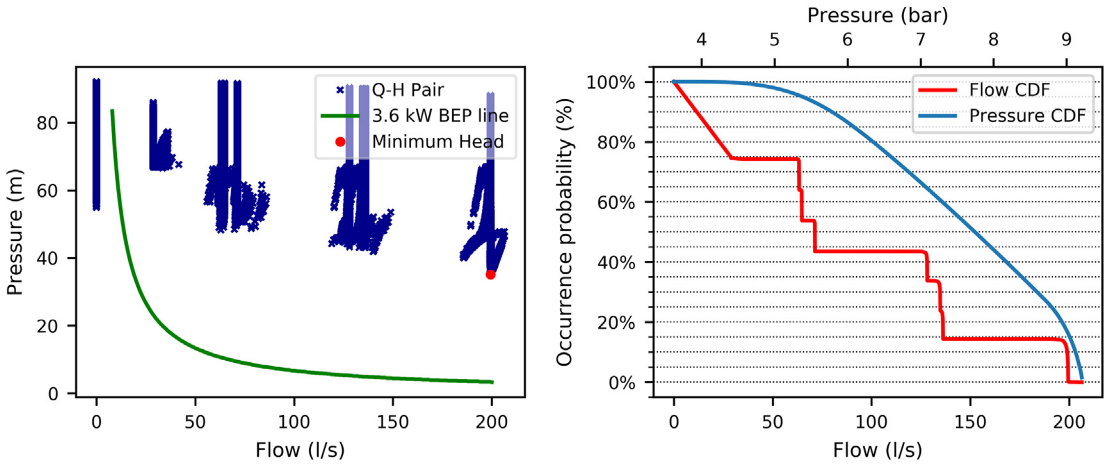


Fig. 4. a) Set of flow-pressure pair of points obtained for the Bernoulli Experiment, best efficiency flow-head line returning 3.6 kW and minimum pressure found in the simulations; b) Cumulative distribution function (CDF) for flow and pressure at the farm.

replacing the diesel generator. The minimum flow demanded was estimated to have an exceedance probability of 73% (see Fig. 4b), which means that the farmer would irrigate for around 73% of the time available between April and September.

The PAT design objective was to ensure the maximum energy requirements of the farm were supplied. Thus, the nominal power was fixed at 3.6 kW. The green line in Fig. 4a represents the flow and head BEPs for all theoretical PATs which are predicted to return 3.6 kW of power under the flow and head conditions predicted at the farm, and considering a 55% global plant efficiency (0.65 PATs hydraulic efficiency + generator efficiency and 0.85 to take into account the hydraulic regulation losses) [43]. In order to have the maximum energy requirement each time that the farmer irrigated without affecting the activity, the nominal flow through the PAT was fixed as the minimum flow estimated to be required by the farmer, 25.4 l s^{-1}. For this flow value, the head required to return 3.6 kW was approximately 26 m.

The farm irrigation time was estimated at around 73% of the irrigation season, using the flow prediction methodology of Crespo Chacon et al. [20,21]. The minimum head that allowed the energy production was present 99% of the irrigation time. Thus, the energy storage system would ensure the supply in those periods where no head was available for MHP production. The size of the energy storage system was defined according to this lack of head found in the very intensive irrigation periods. This head absence was predicted to occur in July and August. Considering the most intensive irrigation periods as being concentrated in one week in July and one week in August, the backup system was designed to have capacity for around two and half hours of maximum energy requirements. Once the size of the storage system was defined, the installation cost was then estimated.

Electromechanical devices [37], including PAT, generator and PRV, civil and electrical works [20], energy storage system and heatsinks to dissipate the excess energy produced, and design costs were included in cost estimations. The energy storage system and energy dissipation costs were accounted for using market prices, and design costs were assumed to be 20% of the installation cost, as the consultancy fee earned by the engineering firm. The final cost was estimated at €21,318.

The operation time at the farm was estimated at up to 3199 h per annum. During the irrigation time, in previous years the diesel generator was working. With this operation time, the annual diesel volume required by the generator was estimated at 3839 L. The economic savings were therefore predicted as approximately €2956 per year, achieving an attractive payback period of 7.2 years. Furthermore, the environmental savings which could be achieved was estimated at up to 11 t eCO_2 per annum.

3.2. Installation and actual performance measurements

The plant was constructed during March 2019, starting its operation in April 2019 at the same time that the irrigation activity at the farm commenced. The final cost of the plant was €22,350, which included the devices for the plant to operate correctly and ensuring the energy demand. Different devices and views of the plant can be seen in Fig. 5. A cost breakdown of the estimated costs compared to the actual can be seen in Table 4.

During the first month of operation, the monitoring system was not functioning fully and the data during April 2019 was not recorded. The irrigation activity in 2019 lasted until the end of September at the farm. The monitoring system allowed remote access to the live data, daily summaries or historic register (see Fig. 6), which permitted a constant oversight of the plant. The total operation time recorded between May and September was 2443 h, to which the irrigation time in April should be added (but was not recorded). The total energy demanded in this period amounted to 222 kWh, which was supplied entirely by the pilot plant. The diesel saved was estimated at 2932 L. Considering the mean diesel cost for the 2019 irrigation season, the economic savings were €2,258, not including activity in April.

The energy demanded by the farmer between May and September and the energy produced by the PAT can be seen in Fig. 6. It can be observed how the production was similar to the demand most of the time. Regarding the energy demand of the farm, it can also be seen that this was generally lower than the maximum energy considered (3.6 kW), although it was demanded at some stages of the irrigation season.

Considering the plant operations, both hydraulic and electrical regulation were tested. During the first part of the irrigation season (May and June) the plant operated using just the VSD (ER). From July until the end of the season, HR was used together with the ER, as the VSD could not be disconnected, setting the PRV installed upstream the PAT. This was done due to the greater flow fluctuations during the intensive irrigation period, encompassed between July and August. The main purpose of this configuration was to protect the installation from high fluctuations that could impart any damage. Setting the PRV, the inlet pressure at the PAT was controlled, thus protecting the installation against high fluctuations

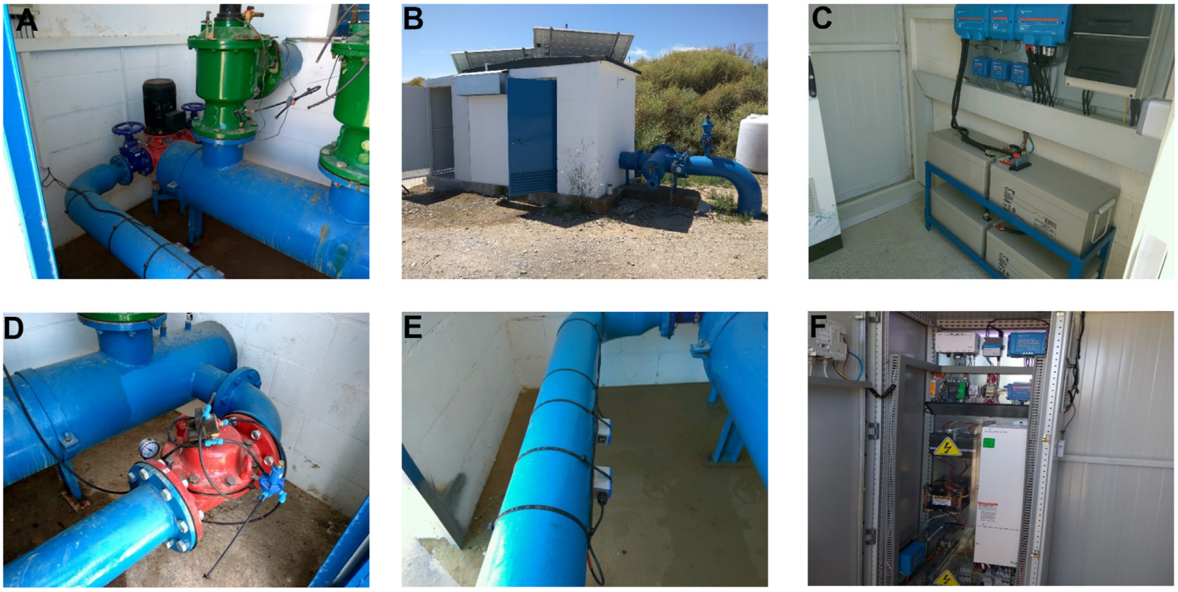


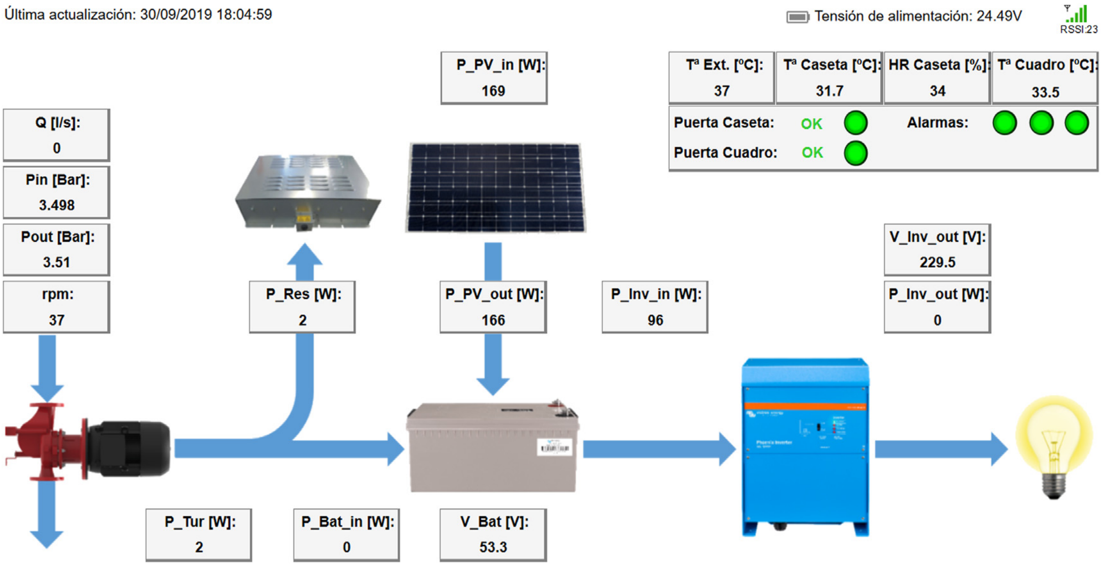
Fig. 5. a) view of the PAT (in red) installed on a bypass; b) safety house, main distribution pipe, heatsinks and solar panels; c) Set of batteries used to store the energy; d) Pressure reducing valve installed upstream the PAT; e) Ultrasonic flow meter used to read the flow elaborated; f) Enclosure where the dataloggers and charge regulators were installed.

Table 4
Actual installed and estimated cost breakdown for main cost categories.

Element	Actual	Estimated
Electromechanical	4890.00 €	3531.78 €
Civil, plumbing	4199.00 €	7144.78 €
Electric (inc. Load controllers)	5844.00 €	4644.14 €
Batteries + heat sinks	1699.00 €	2444.30 €
PV	425.00 €	–
Consultancy + commissioning	5293.00 €	3553.00 €
Total	**22,350.00 €**	**21,318.00 €**

of the operating conditions. Due to the seasonality of the activity and the variation of the weather and crop irrigation requirements, the flow fluctuations along the campaign were quite significant. This variability in the working conditions provides one of the main drawbacks of using PATs in this setting, as their performance can be greatly affected in the absence of a regulation system.

Using just ER presented problems when the variations in pressure were high, due to the lack of devices controlling the inlet conditions. However, when the HR started regulating the inlet pressure using a PRV upstream, the operation conditions of the PAT were stabilised. This difference can be seen in Fig. 8, in which the PAT flow, inlet and outlet pressure were represented in May and July. The fluctuations of the inlet pressure found in May were larger than in July, therefore affecting the working conditions of the PAT as well as its rotational speed. Thus, the employment of ER alone in networks with large fluctuations would need to be accompanied by hydraulic control devices to regulate the inlet conditions in order to maintain the integrity of the installation. This fact would increase the plant cost, hence affecting the investment viability. Therefore,


Última actualización: 30/09/2019 18:04:59

Tensión de alimentación: 24.49V

RSSI:23

Q [l/s]: 0

Pin [Bar]: 3.498

Pout [Bar]: 3.51

rpm: 37

P_PV_in [W]: 169

Tª Ext. [ºC]: 37

Tª Caseta [ºC]: 31.7

HR Caseta [%]: 34

Tª Cuadro [ºC]: 33.5

Puerta Caseta: OK ●

Puerta Cuadro: OK ●

Alarmas: ● ● ●

V_Inv_out [V]: 229.5

P_Inv_out [W]: 0

P_Res [W]: 2

P_PV_out [W]: 166

P_Inv_in [W]: 96

P_Tur [W]: 2

P_Bat_in [W]: 0

V_Bat [V]: 53.3

Fig. 6. Plant synoptic shown at the monitoring platform displaying live data.

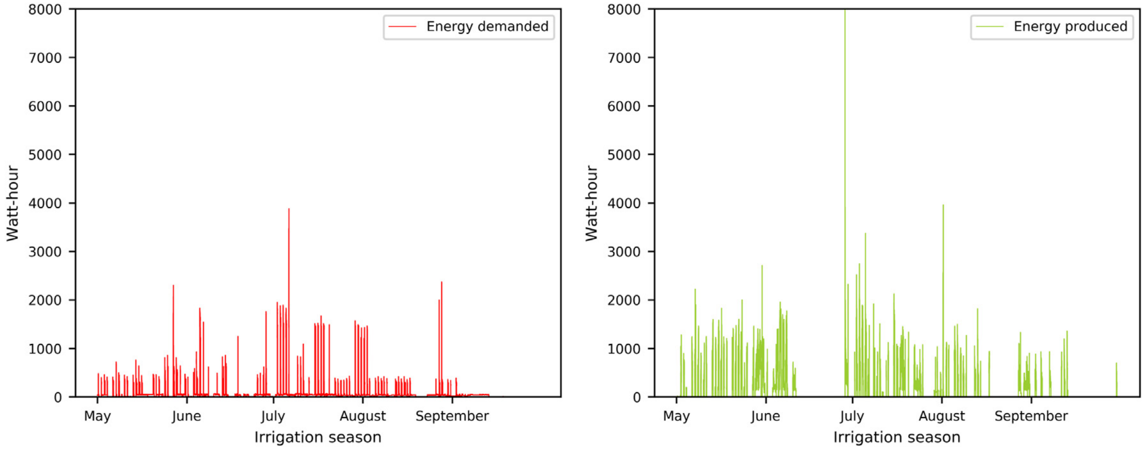


Fig. 7. Energy demanded at the farm and energy produced by the PAT during the 2019 irrigation season.

HR schemes on their own seem more appropriate for plants at farms in large pressurised irrigation networks. Moreover, the combination of ER and HR could improve even more the operation of PAT installations. On the other hand, this would require a greater investment, which is not always possible. HR showed a performance about 3% better than ER. With regards to the cost comparison between both solutions for this specific installation, HR was over 60% cheaper than ER. Nonetheless, this finding could not be considered universal for every installation, as the cost of PRVs increase as per the diameter of the installation, while the VSD would have a similar cost.

Considering the actual cost of the plant taking into account only the required devices for the plant operation, the payback period was estimated at 9.9 years, i.e. excluding data monitoring system. Moreover, 100% of the GHG emissions were avoided, which were close to the 8.4 t eCO_2. If the predicted/irrigation time for April was used to quantify the whole season benefits, 191 h more should be added to the time recorded. Thus, the emissions and diesel avoided raised up to 9.1 t eCO_2 and €2,434, dropping the payback to 9.2 years. A summary of the results obtained at the design stage and the actual results recorded can be seen at Table 5. The monthly results can be seen graphically in Fig. 9.

The annual volume applied to the crops are not always exactly the same than the theoretical irrigation requirements and usually farmers apply deficit irrigation. This effect is common in the area and can be explained by factors such as limitations in the water allocation by the water authority or the irrigation costs. This explains the difference between the number of hours of actual and theoretical irrigation in some months of the year.

4. Discussion

Several measures have been proposed in literature and tested in practice in order to reduce the energy dependency of irrigation networks achieving important results in some cases. Nevertheless, most of these studies analysed the energy dependency of the irrigation distribution network, which is the largest overall energy consumer in an irrigation district. However, these have not considered the energy requirements at farm level. Farms often require energy to carry out the irrigation activity on the farm, either for water filtering, automatic fertilisation or boosting water pressure. In addition, these farms can often be remotely located, not having access to the electric grid, and therefore necessitating the use of other sources to cover the energy demand, most commonly a diesel generator.

For this particular pilot installation, the irrigation requirements increased as the irrigation season went on, therefore incrementing the farm operation time. This fact was also noticed in the data monitored. During the beginning of the season, the farmer mostly irrigated during the daytime, thus not demanding energy at night. This trend then changed for those hotter periods between July and August, in which long night periods of energy demands were also recorded. Analysing the amount of energy requested for day and night-time, a considerable difference was found. While it is true that during the daytime the demand was significant, oscillating between 1 and 2 kW in most of the cases, and reaching peaks of almost 4 kW for some hours, it dropped for the night period to around 40 W. This was related to the habits practised by the farmer. During the daytime, energy was used for one or two fertigator pumps, for the filtering station and for an air compressor, according to the farm requirements. Most of these devices were not used during the night-time, typically only energy the filter station was required, which consumed a small amount of energy. This energy was previously supplied by the 6kVA diesel generator, which worked for the entire night-time just to feed this small output. Thus, a significant amount of diesel consumption was removed, generating valuable economic and environmental savings. In addition, as just a small amount of energy was demanded during the night, the bypass where the PAT was installed was closed as the batteries were able to feed this small energy output. The differences in energy demand for day and night-time can be seen in Fig. 9, as well as the flow, inlet and outlet pressure of the plant during a day in July. If the energy demand was needed to be increased during the night-time, the bypass could be open and the turbine could work, thus ensuring the energy supply during the whole period. This an important advantage found when this solution was compared to solar energy, as the generation for this last one would be limited to day hours.

On the one hand, the demand is very low for the first hours of this July day (0–7am), with about 40 W consumed. At this time, the turbine is not working, as can be noticed in Fig. 8b, since the flow is zero. An increase in the energy consumption coincides with beginning of the working day, when the some of the farm level devices were switched on and the bypass open for the turbine to start working again. After a few hours, the consumption again dropped to almost none and kept constant in small values of around 40 W for the rest of the day. The turbine kept working to charge the batteries and recover the energy consumed during the previous night. Thus, the plant ensured the local energy demands were met at each moment, avoiding the use of diesel and leading to

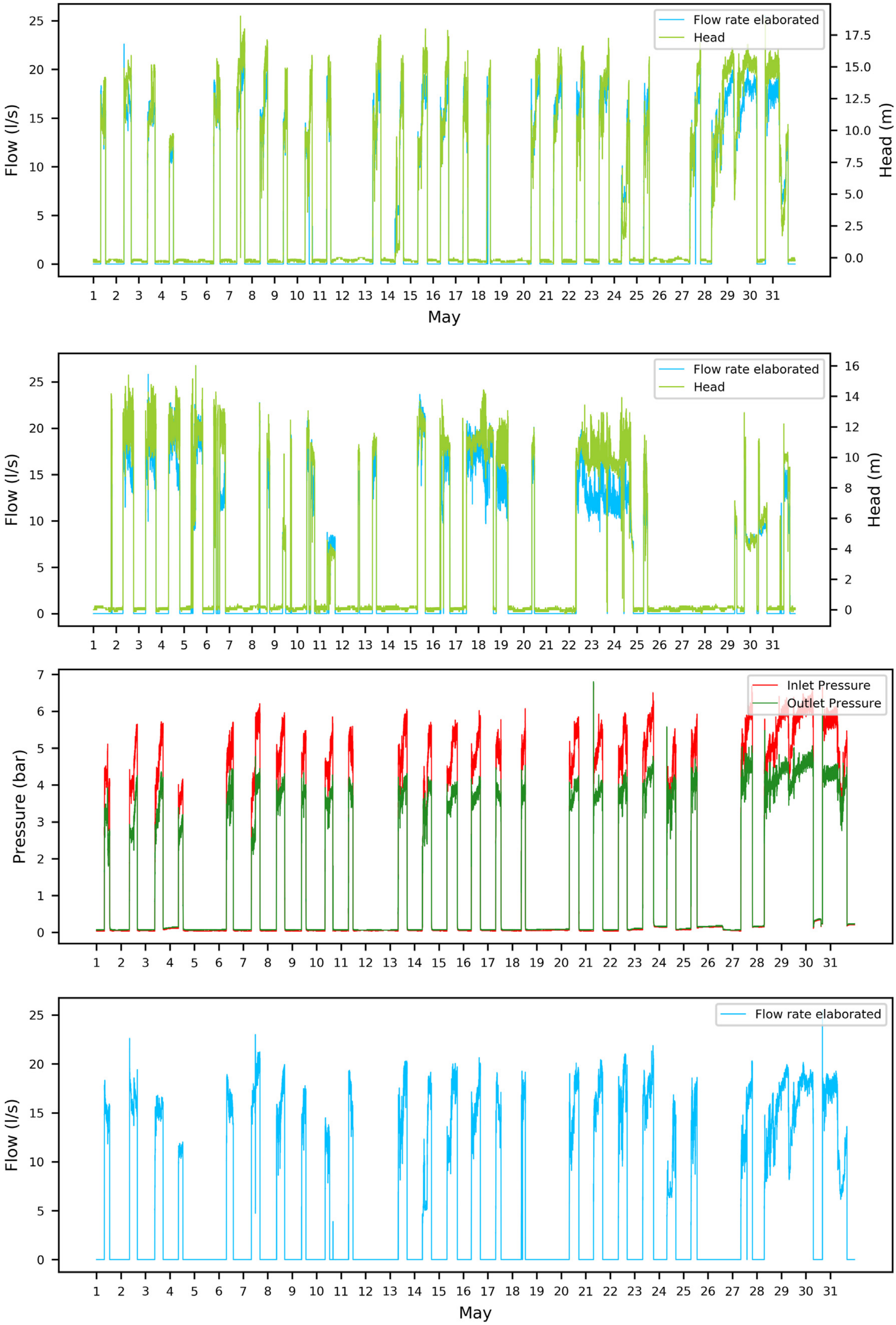


Fig. 8. PAT working conditions for ER (May) and HR (July) registered during the irrigation season: a) Flow-Head in May and July; b) PAT Inlet pressure – Outlet pressure and Flow in May; c) PAT Inlet pressure – Outlet pressure and Flow in July.

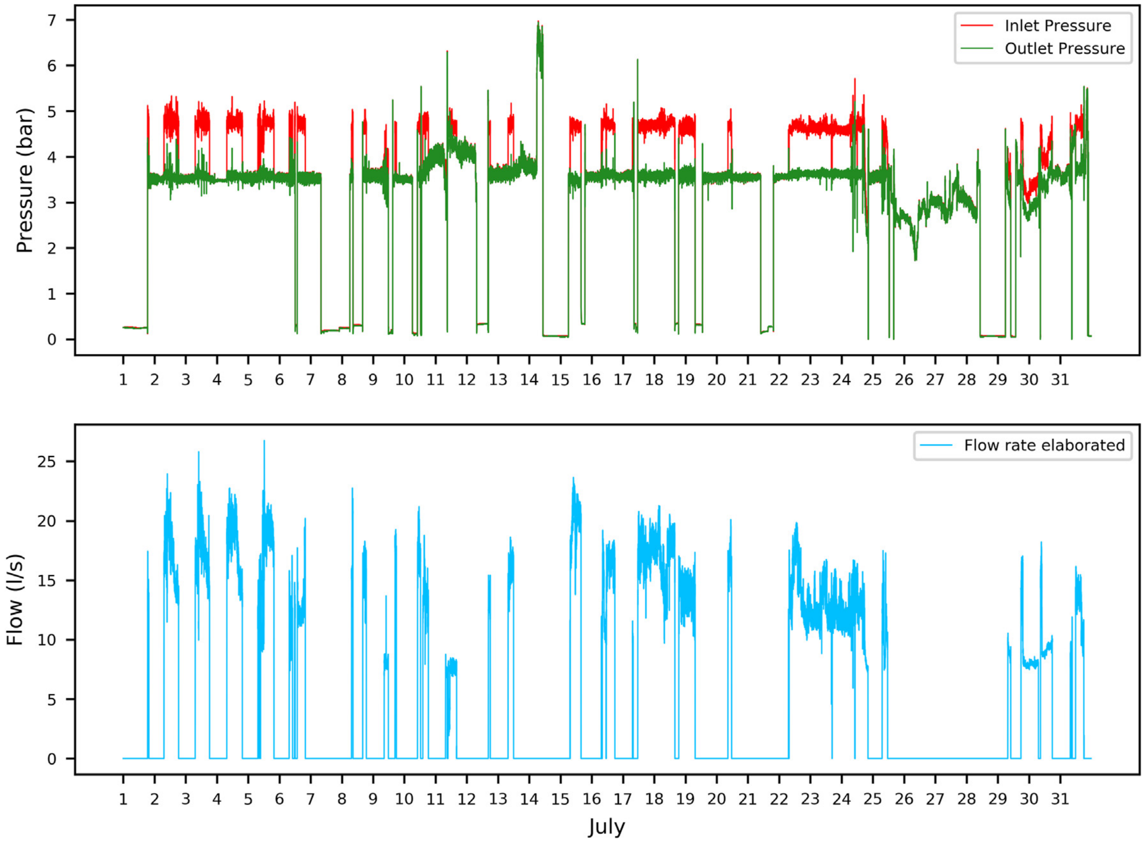


Fig. 8. (*continued*).

Table 5
Summary of the theoretical and actual results. * actual operating time in April not recorded and theoretical value is used in calculations of total time, costs and savings.

	Month	Theoretical	Actual
Operation Time (hours)	April	191.2	(191.2)*
	May	644.5	420.4
	June	682.0	386.3
	July	684.1	689.0
	August	605.5	642.0
	September	391.7	305.2
	Total	3199	2634
Savings	Cost (€)	21,318	22,350
	Litres	3839	3161
	€	2956	2434
	t eCO_2	11.0	9.1
	PP	7.2	9.2

the benefits already explained.

A seasonal evaluation of the plant global efficiency was accomplished. The mean efficiency obtained was 29.5%, which is considerably lower than the 68% given as the peak efficiency of the PAT selected and the peak of 55% assumed in the design and performance estimation process. The fluctuation of the available flow and head conditions in the network has been reported in several studies as one of the main factors affecting the system efficiency for PAT installations. In low intensity irrigation periods, high head values reached the hydrant due to the low flow demands in the network. Hence, the average efficiency obtained in May and June, when the PRV was not working, oscillated around 29.5%, reaching its minimum in June, with an average efficiency of 28.3%. The efficiency increased in July, when the PRV began operating, reaching a monthly average efficiency of 32.1%. Nevertheless, the mean value obtained for August and September was intentionally decreased down to 26.5% and 26% respectively. The efficiency in these months could have increased up to design values if the PRV setting value would have been adjusted upwards, which was reduced from July to August due to the low energy consumption at the farm, hence limiting the energy production to values that were closer to the farm demands. Nonetheless, it can be seen how the working conditions and the efficiency, even for a low efficiency, was kept permanent even when the network operating conditions underwent significant variance (intensive vs non-intensive irrigation periods). HR showed a better regulation of the operating conditions for high fluctuations. Although in this case, ER and HR worked together, it could be said that for large variability of the operating conditions HR could independently operate whilst ER could suffer some damage (due to an overspeed) and affect the installation performance. The plant efficiency variation can be seen at the top of Fig. 10, while the flow diverted for such efficiencies during the whole season can be seen at the bottom in Fig. 10. Overlapping both images, it could be deducted how the unstable conditions, caused by the lack of hydraulic regulation in the inlet, affected to the performance of the system. The inlet pressure is oscillating along the whole range of the head values, going from 0 (when not irrigating) to more than 7 bars (while irrigating). From the end of June onwards, the inlet conditions were regulated as aforementioned. The analysis of the demand for the first two months indicated a very low energy consumption during most of the time (97 Wh on average for May and June). These high demands were concentrated in the central hours of the day but did not reach 2 kW and lasted for

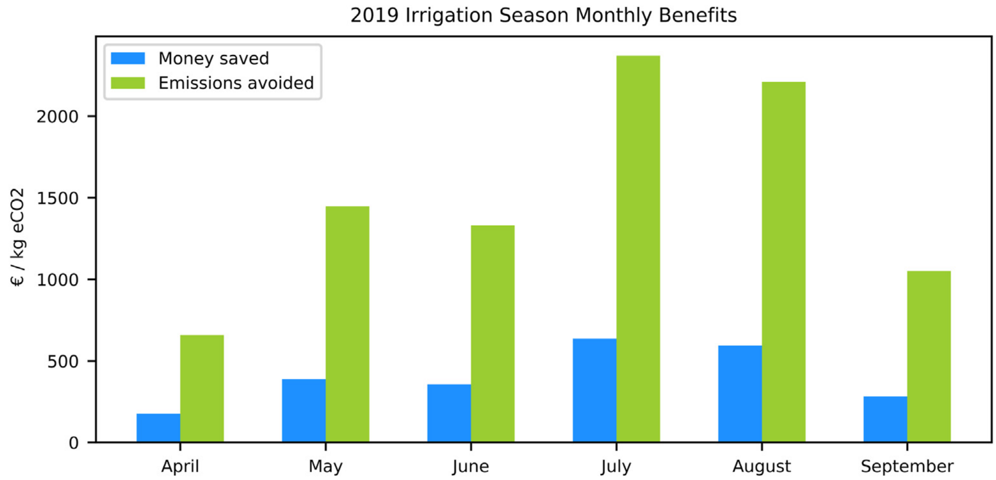


Fig. 9. Graphic summary of the 2019 annual economic and environmental savings of the installation.

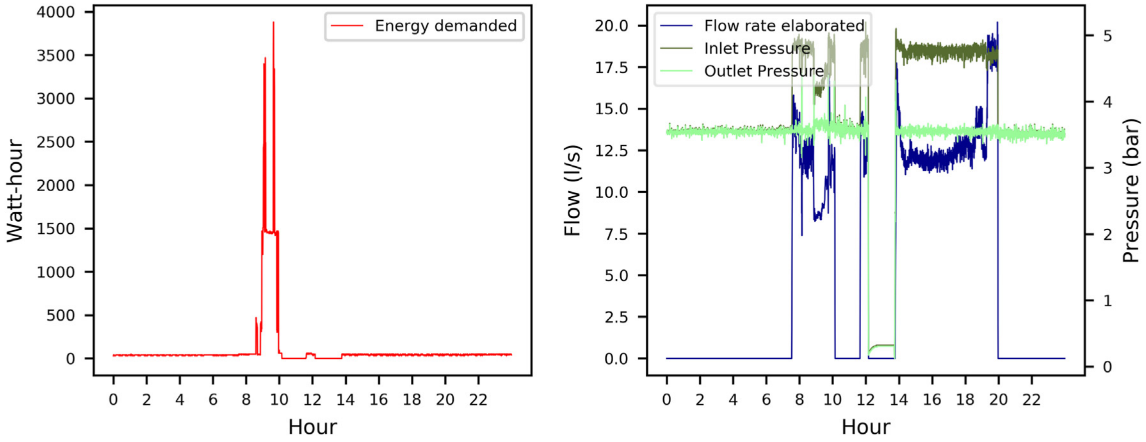


Fig. 10. a) Hourly energy demand for a characteristic day of July; b) Plant working variables for a characteristic day of July.

only a few hours each time. Thus, when the HR was started using the upstream PRV, the inlet pressure was fixed to 47 m, therefore allowing a maximum head of 12m (service pressure of 35 m) and limiting the capacity of production of the PAT. From July forwards, it can be appreciated how the inlet head was regularised, being almost constant when the installation worked (bypass open, day time) and decreasing down to 35 m (service pressure) when the installation was stopped but the farmer irrigated (bypass closed, night-time).

It can also be noted in Fig. 11 that there was a gap in the power production in June. This was due to a maintenance works carried out at the plant caused by a blockage of the turbine by mussels. This blockage occurred as a result during an exceptional maintenance event in the network at the filtering station of the irrigation district. Nonetheless, although the PAT was stopped the plant kept working during this period, supplying the farmer's energy demand using the solar panels and batteries, as these requirements were low enough to be satisfied with the energy produced by these in June. This would not have been the case had the blockage occurred in July or August, since the demands grew as can be seen in Fig. 7.

The inlet pressure for both ER and HR can be seen in Fig. 12 when the bypass was open in both cases. However, this was already considered in the design phase, and the batteries satisfied the demand required. Although the power production capacity was lowered by using the HR, it could be easily increased by raising up the pressure setting of the PRV (i.e. up to 55m, where the PAT would provoke a 20m head) if the farmer's energy requirements were greater. However, the mean consumption was 91 Wh during the whole irrigation season. Higher energy demands would have increased the global efficiency of the plant, since the PAT would work closer to the BEP for which it was designed.

Two aspects could be highlighted from this analysis. On the one hand, the low energy demanded at the farm could be translated into a low global efficiency, as the plant was designed to feed the maximum energy requirements (3.6 kW). If the future demands of the farm are kept this low, it could be deduced that the plant was oversized. In order to obtain greater efficiency for such small power outputs, a smaller PAT could have been installed. Otherwise, if the energy demand increased to values closer to the maximum energy requirements considered during the design, the PAT installed would work with a global efficiency closer to the maximum. The installation of a slightly larger or smaller PAT would not greatly affect the economic performance of the plant, as the cost of the electromechanical devices would not significantly differ from one power output to other at this scale. However, a smaller PAT could impact on the plant efficiency.

On the other hand, it has been shown how the stabilisation of the inlet conditions had an important role in the PAT performance. High variations of the flow and head with no hydraulic control would result in a dramatic variation of the PAT working conditions,

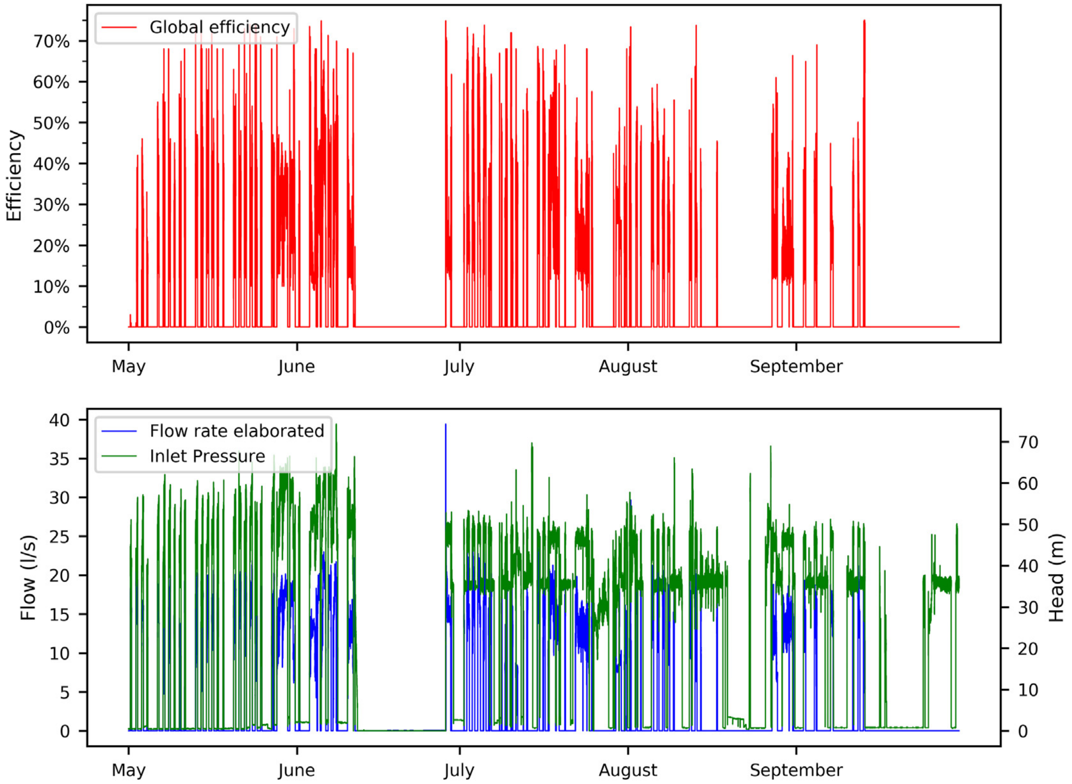


Fig. 11. Global plant efficiency for the data monitored during the irrigation season, depending on the flow rate elaborated.

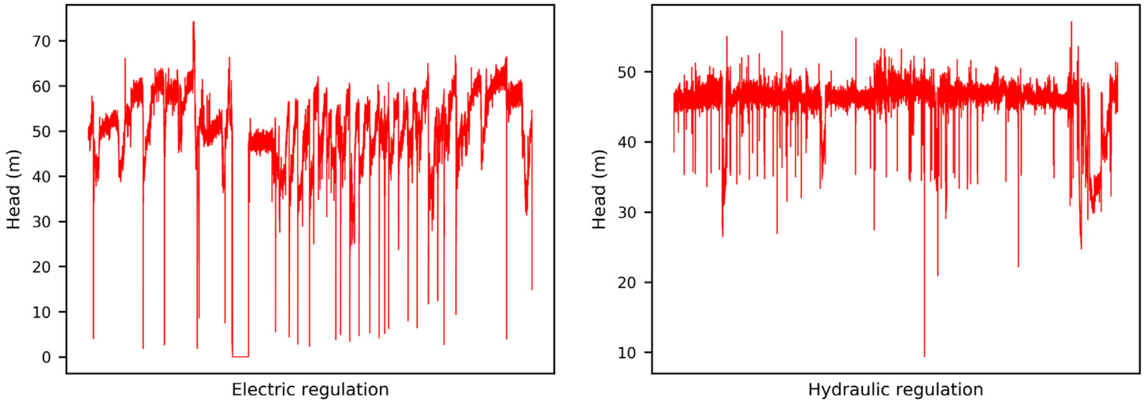


Fig. 12. Inlet head variations registered when ER (May and June) and HR (July to September) operated.

and hence of its performance. High variations of the flow and head with only electrical regulation was also found to be insufficient to maintain a high performance. This fact could even affect to life span of the installation, as in many occasions the PAT and the generator could work under conditions much greater than specified by the manufacturer.

The theoretical approach considered 55% as the maximum efficiency, which has been demonstrated as conservative when compared to the actual maximum, 68%. Despite the fact that mean efficiency was lower, this could be increased if the demand required at farm level was greater, by setting the PRV at a higher pressure downstream.

Lastly, in the analysis carried out above the cost of the diesel generator was not considered in the economic analysis as it was already in existence at the pilot site. However, this may not be the case in every scenario where MHP potential exists at farm level. Considering the cost of the generator used at the farm and the diesel required annually, the payback period of the PAT to cover such investment was re-estimated. On the one hand, the total cost of the plant was reported as €22,350. On the other hand, the 2018 model of the generator used at the farm was found to have a cost of €5151. If this capital cost was subtracted from the total cost of the PAT plant and the annual savings including April were taken into account, the payback period would decrease down to 7.1 years.

5. Conclusions

The existence of excess pressure in large pressurised irrigation networks has been assessed by different authors for the application of MHP energy recovery. MHP has been shown here to be an attractive solution to supply local farm-level energy demand, which is required when the farmers need to irrigate. The conditions required for MHP production are subject to large fluctuations in irrigation networks, which directly affects the energy production achievable. However, this can be partly addressed with a deep analysis of the conditions available in each case and the use of regulation and energy storage systems. The excess pressure found at the farm suffered significant fluctuations, going from almost no excess pressure to more than 50m across the season. Nevertheless, as the main aim of this MHP pilot plant was to replace a diesel generator, the energy demands could be satisfied by just taking advantage of a small amount of the head available. During the design analysis, it was seen that there was a small likelihood of no excess pressure being available during July/August, which necessitated an energy backup system.

The theoretical results predicted that the plant would be able to completely replace the diesel generator, leading to benefits in both, environmental and economical fields. 11 $teCO_2$ were predicted to be avoided annually and around €3000 saved. Once the plant was constructed, the results were contrasted with the actuals performance recorded. The actual plant supplied the entire energy requirement at the farm, saving almost 3000 L of diesel from May to September, which offset 8.4 $teCO_2$ and saved over €2250. These results increased up to 9.1 $teCO_2$ and more than €2400 when the irrigation time estimated for April was considered, decreasing the payback period from 9.9 to 9.2 years. Finally, it was observed that HR was necessary instead of or to complement ER for high fluctuations of the PAT working conditions, as the global efficiency was affected and the life span of the plant could be reduced. Moreover, the global average efficiency obtained was significantly lower than the maximum efficiency. If the energy demands kept close to the small values registered during the 2019 irrigation season, it could be deduced that the plant was oversized. On the other hand, the power installed would allow an increase of the farm's demand, as the production capacity of the plant is greater than the production required for the last campaign. This fact would allow the farmer to raise the consumption. Thus, if the demands increased to values closer to the maximum energy requirements (3.6 kW) the global efficiency of the plant would grow and the size of the plant would be justified. Finally, fostering the adoption of sustainable solutions is an essential factor for agriculture in the short-term. Hydropower and PATs have been proven as a viable solution to satisfy the power requirements of irrigation activity at farms level, while also avoiding the use of fossil sources and all their negative impacts to the climate change. This approach gives an added value in the market to the agricultural products cultivated, which would be even bigger than the economic savings in diesel since consumers increasingly value food produced in a sustainable way. The use of diesel generators at farm level is widespread in large irrigation networks and this research presents a great opportunity to remove the impact of this activity on the environment.

CRediT authorship contribution statement

Miguel Crespo Chacón: Design, Conceptualization, Methodology, Writing. **Juan Antonio Rodríguez Díaz:** Installation Design. **Jorge García Morillo:** Database manipulation. **Aonghus McNabola:** Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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