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Hydro-power energy recovery in pressurized irrigation networks: A case study of an Irrigation District in the South of Spain

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ABSTRACT

As a result of climate change, higher irrigation water demands are predicted in the future in pressurized irrigation networks. This will result in larger energy requirements and greater CO_2 emissions levels for irrigation networks powered by pumping systems. Therefore, measures to counteract this growth in energy and CO_2 emissions in the agri-food sector, such as energy recovery using hydropower, are becoming imperative.

The Bembézar Margen Izquierda (BMI) Irrigation District, in Southern Spain, has been analysed and simulated for several water demand scenarios using a model based on the hydraulic simulator EPANET. Results show that a substantial amount of energy used for the distribution of irrigation water can be recovered. Flows and heads available at four different locations in the network showed suitability for the installation of one traditional Francis turbine and three Pumps-as-turbines (PAT).

The methodology used was divided into four phases. In the first phase, the network was simulated with all hydrants simultaneously open and the best locations to install HPP (Hydro Power Plant) were assessed. In the second phase, the maximum, minimum and mean flows and available head values per month at each HPP location were obtained using on-demand simulations applying the Clément methodology. In the third phase, the flow and net head available in the turbines were transformed into energy. In the last phase a feasibility study was carried out through three indices. Applying this methodology, the maximum recoverable energy was estimated as 270.5 MW h and the maximum carbon savings potential was estimated as 108 t eCO_2. These technologies represent a positive competitive advantage for agricultural production reducing the carbon footprint and therefore improving the sustainability of the agricultural production.

1. Introduction

In pressurized water distribution systems, the dissipation of energy to avoid excess pressure is typically conducted using Pressure Reducing Valves (PRV) or break pressure tanks. The fitting of a turbine in a pipe network, instead of a PRV, is an attractive alternative to reducing excess pressure while also generating electricity, evidenced since the late 1980’s (Penche, C., 1998). Recently, the concept of energy recovery using micro-hydropower has been studied in much more detail by many different authors, and primarily in the drinking water supply setting (Ramos and Borga, 1999; Gaius-obaseki, 2010; McNabola et al., 2011; Carravetta et al., 2012; Lydon et al., 2017a).

The energy savings potential at an individual excess pressure site is typically small (2–20 kW). However, many traditional turbine technologies cannot be miniaturized to such capacities without prohibitive costs. This drawback has been solved partially with an innovative technology named Pump-As-Turbine (PAT). The fundamentals of PAT theory are well established in Carravetta et al. (2018). PATs are pumps operating in reverse to produce energy instead of consume it (Ramos and Borga, 1999; Carravetta et al., 2012; Fecarotta et al., 2015). This is a well-known concept in the water industry and is an efficient method of generating power as well as recovering energy while contributing to savings (McNabola et al., 2014).

Although the peak performance of a PAT is typically less than that of a conventional turbine, the cost can be up to 10–20 times less (Power et al., 2016). From the economical point of view, it is often stated that the capital payback period of PATs in the range of 5–500 kW is two years or less (Derakshan and Nourbakhsh, 2007; Carravetta et al., 2013). Other authors have estimated this value between 2.5 and 6 years (Marchis et al., 2014), and 4.7 years in a recent study (Lydon et al., 2017a). The large differences in cost reported in literature are due to the influence of civil works, piping, and/or electronics, as well as economies of scale. The use of conventional turbines in a micro-hydropower (MHP) setting typically yields a payback of 8–10 years in

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economically viable cases (Corcoran et al., 2013). All these works have focused on urban water supply networks and not on the irrigation sector, which usually has higher fluctuations in water demand, as well as different seasonal and daily demand patterns.

A turbine is often designed to operate at a relatively fixed flow rate and head which correspond to its maximum efficiency. As flow or pressure change from this best efficiency point (BEP), the performance of the system is reduced. This results in less energy being generated and can increase significantly the payback period of the installation. Nevertheless, most conventional turbines have low sensitivity to changes in flow rates. Variations of ± 50% will not imply significant drops efficiency. However, the range of flow rates over which a single PAT can operate is usually much narrower than in a conventional turbine and it should be carefully selected to obtain the best possible efficiency (Fontana et al., 2012). The efficiency of a PAT drops abruptly with small flow variations. Previous research in drinking water supply networks has shown that when the flow deviates +20% from the BEP, the performance is reduced by up to 22%. When the deviation is −20% the performance reduction drops by 70%. This aspect highlights the need for PAT operation to be controlled close to the BEP (Lydon et al., 2017a). Flow fluctuations of this magnitude (20%) are commonly found in irrigation networks. Preliminary studies were carried out considering the annual average flows (Estrada and Ramos, 2015). Other researchers analyzed in more detail the flow variations and calculated the maximum theoretical energy recovery coming from the energy dissipated in the network because of friction losses (Pérez-Sánchez et al., 2016).

Energy recovery in irrigation has significant relevance to the sector since many farmers cannot apply the full crop water needs due to the high cost of the energy. This high cost forces farmers to concentrate the irrigation when the cost of the energy is lower. Previous investigations have shown that high energy requirements have led farmers to apply less water than the maximum theoretical irrigation needs, thus applying deficit irrigation as a strategy to maximize profits versus the traditional maximization of crop yield (Rodríguez Díaz et al., 2011). Under this scenario, methodologies to reduce the energy consumption are critical such as: irrigation network sectoring (Fernández García et al., 2013), critical hydrant detection (Rodríguez-Díaz et al., 2012), irrigation scheduling in turns (Moreno et al., 2010), solar pumping (Mérida García et al., 2018) or the use of variable speed drives (Fernández García et al., 2013). But once these measures are undertaken, the recovery of the energy inherent in excess pressure in the network should be investigated. Hydropower energy recovery in irrigation is still largely unexplored and requires further investigation. All these methodologies should be considered as useful tools for both, the reduction of energy consumption and the recovery of the excess energy in pressurized irrigation networks. This energy generation could contribute to reducing the exploitation costs of these systems, increasing the competitiveness of agricultural production and reducing the carbon footprint of irrigated crops.

The scope of this work was to quantify the potential of hydropower energy recovery in a pressurized irrigation network, assessing its technical and economic feasibility. The maximum flow circulating in the network and available head were estimated using statistical methods and computer simulations. Pressure regulator valves (PRVs) were used to represent the head-loss that would be induced by a turbine placed in the network to reduce pressure and recover energy. The economic analysis was conducted in terms of Power (kW), Energy recovery (kW h) and potential revenues of recovered energy (€), as well as its economic viability through the payback period, the power index (€/kW) and the energy index (€/kW h). The analysis was applied to a real case study during one irrigation season (2014–2015) in Southern Spain.

2. Material and methods

2.1. Study area

The left bank of the Bembézar river irrigation district (BMI) is in the Guadalquivir River Basin (GRB), near to the city of Córdoba (Andalusia, Southern Spain). Average annual rainfall in BMI was slightly higher than 500 mm and potential evapotranspiration was around 1400 mm (Rodríguez Díaz et al., 2007b). The main crops in BMI (4000 ha) are Citrus (47%), Maize (26%), Olive trees (10%), and Sunflower (3%) (Fernández García et al., 2014a).

BMI is characterized by a steep topography with hydrant elevations ranging from 58 m to 103 m (Fig. 2a). This branched irrigation network is comprised of 28 hydrants designed to supply 1.2 $\mathrm{Ls^{-1}\,ha^{-1}}$ with a service pressure of 35 m. Water is conveyed through 220 pipes with a total length of 32 km. Currently the irrigation network is operated on-demand, which means that water is continuously available to farmers. This network is an interesting candidate to assess hydropower energy recovery potential, due to the difference in elevation within the system.

The pumping station (elevation of 93 masl) was originally designed to supply water on-demand and is composed of seven split case horizontal centrifugal pumps. There are 2 types of pumps: A, with lower power to supply water when a few hydrants are open, and B, higher power pumps. There are three pumps of type A (315 kW) and four of type B (800 kW). One of the 315 kW pumps is activated with a variable speed pump (VSP), and the others operate as fixed speed pumps. The sequence of activation is the variable speed pump (VSP) followed by all A and B pumps, consecutively.

2.2. Methodology

The methodology was divided in four phases. A schematic representation of the methodology is shown in Fig. 1. In the first phase, the network was simulated with all hydrants simultaneously open and the best locations to install HPP were assessed. In the second phase, the maximum, minimum and mean flows and available head values per month at each turbine location were obtained using 3000 on-demand simulations applying the Clément methodology (Clément, 1966). This methodology simulated a more realistic scenario than in phase 1, where multiple combinations of open and shut hydrants were simulated across the network, yielding a distribution of flow variations based on flow probabilities. In the third phase, the PAT/turbine sizing was performed according to the flow rates and excess pressure calculated in the HPP locations after the computer simulations. In the last phase a feasibility study was carried out through three indices, the payback period, and the power and energy index.

2.2.1. HPPs locations

The hydraulic simulator EPANET (Rossman, 2000) was used to select the best locations to install the hydropower plants (HPPs). The excess pressures were detected after a simulation considering that all the hydrants were simultaneously open (most unfavorable conditions, which would rarely occur in practice). The locations with the largest excess pressure were selected, starting from the pump station (higher flows). In these locations, pressure reduction valves (PRV) were modeled and set at the value that ensured a minimum pressure of 35 m in the most critical hydrant downstream (Fig. 2b). PRVs were used to represent the head-loss which would be induced by a turbine placed in the network to reduce pressure and recover energy. The same procedure was used in the different branches of the irrigation scheme to calculate the excess pressure within the network without compromising the service pressure in the most critical hydrants.

2.2.2. On-demand simulations

In the previous phase the best locations were selected considering that all hydrants were simultaneously open. However, in on-demand