Energy recovery in a drinking water plant using an innovative micro-hydropower system based on the integration of a Pump as Turbine and an energy storage

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Introduction

European hydrological planning policies have traditionally been based on increasing the availability of water resources and the capacity to regulate them. In the case of the urban water cycle (UWC), these approaches have led to a gradual depletion of the resource (overexploited aquifers), loss of quality of water provisioned, deterioration of aquatic ecosystems and conflicts between users motivated by the existence of conflicting interests. In recent years, water and sewage treatment operators across Europe have been forced to use more energy intensive processes as a consequence of expanding water quality legislation [1]. Metropolises around the world are also facing global change pressures due to climate change and water scarcity, which are making it a challenge to continue to deliver core urban water services without increasing the impact on the natural environment. In addition, much of the water and wastewater infrastructure in the developed world is now over 50 years old and needs replacement, upgrade or repair. The importance of water losses in the overall total distributed water is well known. The amount of water leaked in water distribution systems varies widely between different countries, regions and systems, from 3–7% of distribution input in the well-maintained systems to 50% and even more in some undeveloped countries and less well-maintained systems [2]. Extreme temperatures due to climate change and infrastructure aging will enhance the problem of water leakage and confirm the need to control and reduce leakages in the drinking water networks.

In general, all the above-mentioned threats looming over the UWC shown imply an increase in the energy consumption and operating cost. However, to date, limited analyses of the energy implication of water strategies have been undertaken and energy use is rarely mentioned in urban water strategies, despite considerable public commitment and efforts from individual utilities. It is clear that planners must now consider the energy implications in decision making on the water system. Sustainable solutions to these challenges need to be sensitive to long-term investment needs, but also to increasing energy prices, demands for low carbon intensity solutions, and the need to reduce greenhouse gas (GHG) emissions from urban activities.

The potential of energy savings in the UWC, and in the water transport in particular is very significant. Water is a natural carrier of heat and energy gradients, which could be re-used to improve energy efficiency in several ways. The water-energy needs to be considered at all levels, from the overarching water management (combining smart-water and smart-energy), to new solutions in various steps of the water chain.

LIFE NEXUS project is focus on the energy harvest from the UWC stages than implies water movement: catchment, distribution, collection and discharge. The project is evaluating the technical / economic and environmental feasibility of the energy recovery potential available in the previous mentioned four types of locations by means of Small Hydropower Plants (SHP). Among the different available machines (traditional turbines or adapted machines) LIFE NEXUS demonstration will be focus on the innovative Pump as Turbine (PaT), a type of adapted machine, that is becoming the technological solution for micro-hydraulic projects (≤ 100 kW). The main advantages of these machines are their immediate availability for installation and lower cost compared with conventional machines.

A cutting-edge integration of a PaT machine together with battery storage is being carried out to enhance the possibilities of the energy management. This innovative system will be installed at the entrance of the Porma Drinking Water Treatment Plant (DWTP) located in Valdefresno, a small village nearby the city of Leon (Spain). Once they will be fully operating the energy generated will cover the total energy demand of the installation. This paper is focus on (1) the design of the PaT prototype, including the selection of the pump, (2) the definition of the hydraulic operation and (3) analysis of energetic production and optimization of energy scenarios.

Materials and Methodology

The demosite is located at the DWTP of Valdefresno in León (Spain). The plant is supplied by a diversion of water from the Porma River with a height difference of 16 m. The transport pipe between the diversion dam and the DWTP is approximately 33 km long. The PaT prototype will be located at the entrance of the DWTP, replacing an existing PRV (see Fig.1). The DWTP consists of five treatment stages: (1) Pre-oxidation, carried out with sodium hypochlorite, (2) Coagulation/ Flocculation, carried out by adding aluminum polychloride, (3) Flotation, sludge separation is done in the eight floats, not in decanters, (4) six sand filters (see Figure 11) and (5) final disinfection with sodium hypochlorite. The DWTP annually treats an average volume of 8.146 Hm^3/year.

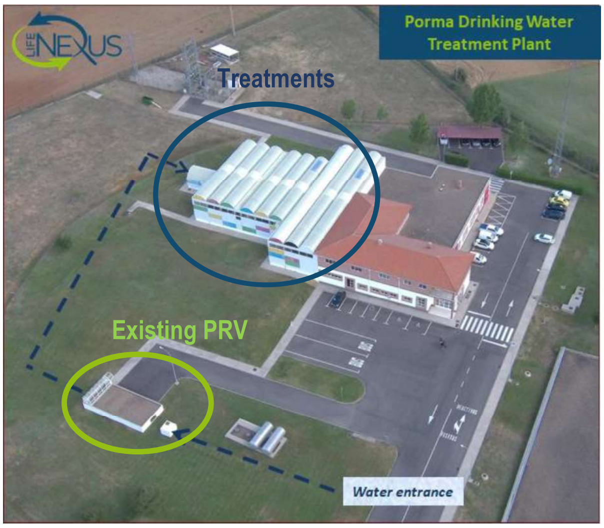

Fig.1. Porma DWTP demosite

Results and Discussion

PaT prototype design and pump selection

The pump was chosen considering the resistance curve at the entrance of the DWTP, with 25.5 kW of nominal power (45 kW maximum power). The information from the projected installation and the estimation of annual energy generated is shown in the table below:

Table 1. Data of projected installation and annual energy generated

Parameter	Value
Average available flow (m^3/h)	853
Average available hydraulic jump (mwc)	18.3
Average hydraulic power available (MWh/year)	372
Average power generated hourly P2 (kW)	28.9
Hours of work per year	8,724
Annual energy generated (MWh/year)	252
Performance with respect to potential	68%
Performance PaT	81%
Averaged turbined flow (m^3/h)	738
Average hydraulic jump in PaT (mwc)	16

To operate the system, it will be necessary to install an inline valve (PRV) downstream of the PaT connected in series with it, and another pressure sustaining valve which enables the regulation of the flows in the PaT's by-pass (see Fig.2):

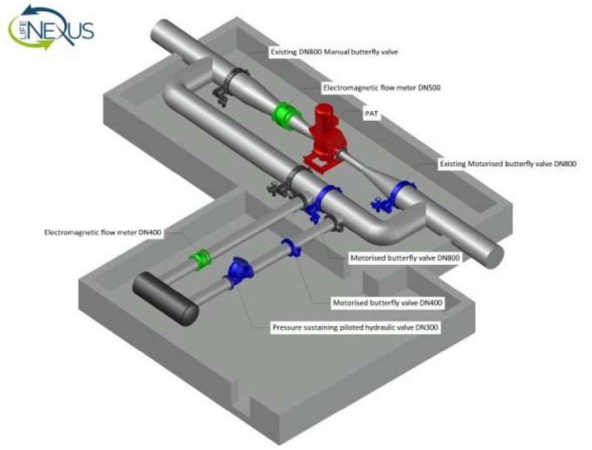

Fig.2. PaT prototype

Proposed installation and hydraulic operation

The pressure sustaining valve in the by-pass has the function of diverting excess flow in the main line. By diverting part of the flow, it manages to fix the flow rate through the PaT, fixing at the same time the jump in this machine and the power generated whilst maintaining the network pressure o within the current operating range. The inline valve has the function of ensuring the necessary downstream pressure, therefore, depending on the scenario; it will regulate its opening to achieve the necessary pressure (see Fig.3):

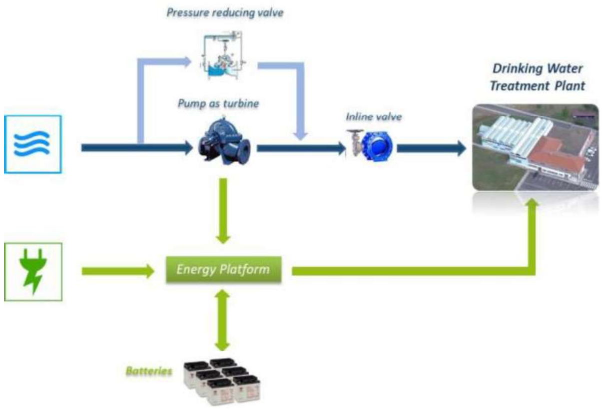

Fig. 3. Hydraulic operation of the PaT prototype

Two hydraulic scenarios of operation have been defined depending on the flow needed by the installation and the averaged turbined flow of 205 L/s (738 m^3/h):

Scenario 1 (Inlet flow ≤ 205 L/s): all flows between 115 l/s and 205 l/s will pass through the PaT and the in line valve, which will be regulating until it can maintain the necessary downstream pressure of 3 mwc (Fig.3). This opening will depend on the demand flows of the plant, but will always guarantee the pressure consigned at the plant inlet. In this scenario, no water will enter the by-pass and, therefore, the pressure sustaining valve in the by-pass will be completely closed.

Scenario 2 (Inlet flow > 205 L/s): in this scenario, a stable flow of 205 l/s (738 m^3/h) will pass through the PaT and the valve in-line will be completely open, being 100% open this valve will not regulate. The downstream pressure of this valve should be 3 mwc, the same as in the previous scenario. In this case, all volumes greater than 205 l/s (738 m^3/h) will go through the by-pass. The pressure sustaining valve situated in the by-pass will regulate its opening depending on the flow which goes through the by-pass and its downstream pressure. This valve's operating range will vary between 54% and 29% of opening.

Analysis of energetic production and simulation of energy scenarios

The analysis of the operation of the PaT system was established together with a system of batteries that accumulate the energy in periods when more energy is generated than consumed by the DWPT. The objective is to study the energetic advantage when renewable energy can be accumulated for its later consumption in the facility, leading to less consumption from the grid, a greater degree of energetic self-sufficiency and a reduction in energy costs. For that, the charge curve (energy demand) of the Porma DWTP was analysed (Fig. 4). As it can be seen, in the Quarter hourly-charge curve over the year, powers of 50 kW are consumed sporadically every two days approximately and mean between 20 and 30 kW of extra consumption on the immediate consumption. This periodic peak consumption takes place in the equipment related to the sand filters washing: backwash pumps and blowers.

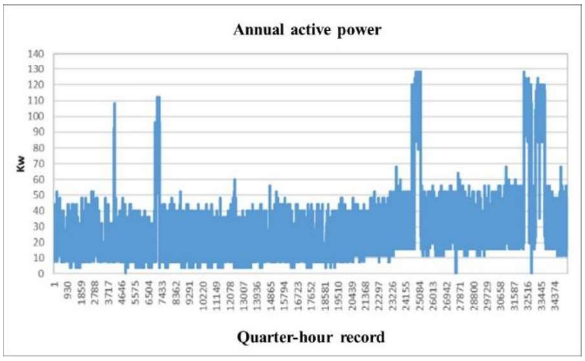

Fig. 4. Charge curve for the DWTP

These machines start up every time it is necessary to clean the filters, which is approximately every two days and they work for 6 minutes, first the pump and afterwards the blower for 6 minutes. As the washing filter system is integrated by 2 lines (pump and blower) which operate alternately, demand is not exactly the same every day. It is about avoiding these consumption peaks, taking advantage of the energy generated in the turbine, which will normally be greater than the immediate energy consumed in the DWTP, accumulating that excess energy in the batteries to make the most of it during that occasional periodic demand. By doing so, it is believed that it would be possible to reduce the peak power required in the DWTP the majority of the year, which means a benefit for the electric grid given that it stabilises demand and a possible benefit for the DWTP reducing the need to contract high powers and thus reducing the energetic cost.

In conclusion, a hybridisation via batteries has been designed, modifying the system through the incorporation of a frequency converter in the head of the four units (2 backwash and 2 blower pumps). A charge regulator has also been included which will be responsible for slowly the batteries slowly and discharging them in in a matter of minutes. Lastly, the batteries have been dimensioned so they can supply the demanded energy for the equipment over the time they are operating.

Simulation of energy scenarios

Usually the energy generated in the PaT is greater than the instantaneous energy consumed in the DWTP so the production will be used to cover this demand (See Fig. 4). The excess energy will accumulate in the batteries to take advantage of it during that periodic punctual demand that corresponds to the consumption peaks of the washing filter system. With the aim of minimizing the network contribution and optimizing the use of energy storage, the behaviour of the PaT-storage system has been evaluated in a dynamic simulation environment (TRNSYS) by carrying out a series of models that represent different configurations and operating scenarios. First, a **PaT model** has been generated, which, depending on the flow rate and its operating restrictions, provides the power and energy generated and, on the other hand, the outlet pressure. For this, we have started from the information of the operating curves provided by the manufacturer:

$$P = 0.0001 \cdot Q^2 - 0.0079 \cdot \mathrm{Q} - 2{,}3928 \quad (1)$$
$$\Delta\mathrm{H} = 0.000029 \cdot Q^2 - 0.012776 \cdot \mathrm{Q} + 7.949 \quad (2)$$

Being P the electrical power output (kW), Q the water flow (m^3/h) and ΔH (mwc). As operating restrictions, it has been considered that the turbine operates in the flow range that goes from 115 l/s and 205 l/s. For higher flow values, the bypass branch is opened to limit the maximum flow that passes through the turbine as explained in the hydraulic scenario 2.

The model's input data are the flow records that enter the DWTP and the hourly energy demand values collected over a year (simulation period, Fig. 4). The model generates as outputs the energy balances and the operating status of each of the systems (operating regime, load level, etc.) including the needs for energy exchange with the grid.

Then, it has been carried out the development of **a model of the total system**. In the TRNSYS dynamic simulation environment, the different models of the elements of the DWTP installation have been integrated: PaT, batteries and different loads (backwash pumps, blowers, lighting, etc.). In this model, the interconnections between the elements have been made and the controllers that guarantee the safe operation of the system have been included.

Two basic operation schemes have been established, depending on the interaction between storage and the rest of the installation (see Fig. 5):

- In the first case (Fig. 5a) it is considered that the battery system exclusively supplies the demands of the pumps and the blower of the cleaning equipment (as initially planned).
- In the second case (Fig. 5b) the battery power can be used to cover the overall needs of the system.

In both cases, the PaT discharges its energy into the internal network of the system, allowing it to power the different loads and charge the battery. Energy imbalances are exchanged with the grid:

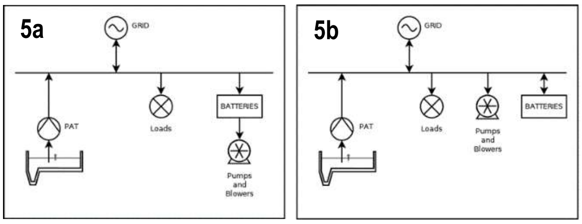

Fig. 5. Basic operation schemes

Figure 6 shows the TRNSYS model used. In each of the cases considered above, the internal control programming is modified to establish the energy flows and the final balances:

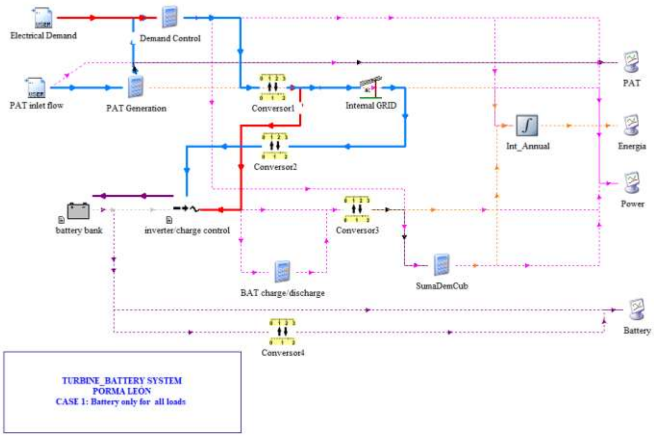

Fig. 6. TRNSYS model. Case 1.

Finally, from the simulation of the developed models, a sensitivity analysis is being carried out, varying the key design and operation parameters (battery size, hours of use of the equipment, weather conditions, etc., allowing the analysis of the flows of energy produced in the different scenarios. This phase is currently under development and will allow establishing the best operating strategies for the system and identifying improvements in the implementation of battery-powered PaT systems in other locations. Note that the simulation data will be verified with the measurements obtained from the data of the real system when it is operational.

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