# Assessment of the potential for energy recovery in water trunk mains

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**Abstract.** The energy efficiency of water supply systems can be significantly enhanced if the existing energy in excess can be recovered instead of dissipated in pressure/flow control valves. A prospective energy recovery solution is the installation of pumps operating as turbines (PAT). However, a previous sound estimation of the potential energy that can be recovered and of the economic viability of such projects needs to be carried out. This is not a straightforward task as it depends on many factors (e.g. hydraulic power, PAT efficiency and cost). In this paper, potential locations for energy recovery in a Portuguese water transmission system are identified and the economic feasibility of installing pumps operating as turbines is assessed. Results have shown that installing PAT can be a feasible solution at the inlet of storage tanks only if available hydraulic power is higher than 50 kW and operating times (during the tank filling) at the maximum power are higher than 100 days/year. Additionally, the economic assessment of the hydropower solution's feasibility is based on several assumptions whose impact on the global results must be further analysed.

## 1 Introduction

Water treatment and transport from the source to the user's tap are energy intensive processes (Lofman et al., 2002), which denotes a significant energy cost for the water utilities. Thus, water supply utilities are currently looking for innovative ways to simultaneously reduce the energy costs and to increase their financial and environmental sustainability, using the existing conditions in their infrastructures. On the other hand, drinking water flowing through trunk mains by gravity often carries more energy than what is actually needed to supply the downstream consumers. For that reason, the excessive pressure must be dissipated in flow control valves (Williams et al., 1998), frequently installed at the storage tanks' inlet (Gallagher et al., 2015). Such energy could be recovered instead of wasted. Replacing an energy dissipation device by a micro hydropower turbine can simultaneously reduce pressure and recover energy (Gallagher et al., 2015).

Zakkour et al. (2002) and the European Small Hydropower Association (European Small Hydropower Association, 2010) estimated an average recoverable power of 17 MW and 20 MW, respectively, in the United Kingdom and Switzerland. Recently, the potential to generate 17.9 GWh per annum in water and wastewater infrastructures in the UK and Ireland was reported (Gallagher et al., 2015).

The assessment of the potential for energy recovery in water and wastewater infrastructures, namely at service tanks, locations of pressure reducing valves and wastewater treatment plants includes: i) the sites identification, ii) hydraulic power estimation and iii) technical and economic constraints analysis (Gallagher et al. 2015). The economic feasibility analysis of the project includes the prediction of installation costs and of payback periods.

The cost analysis of an energy recovery project in a water supply system includes many uncertainties, such as long-term demand growth, diurnal and seasonal demand variations and future cost fluctuations (Colombo and Kleiner, 2011). In addition, some authors highlight the need for new policies to promote the installation of hydropower turbines in order to improve project viability (Corcoran et al., 2013).

Among several solutions to recover the excessive hydraulic power, pumps operating as turbines (PAT) are pointed as a cost-effective solution for energy production (Ramos and Borga, 1999). This technology allows the conversion of hydraulic power into mechanical shaft power with considerable efficiency and with lower initial investments than the hydropower conventional units (Williams et al., 1998). There are some examples of pumps operating as turbines installed in water supply systems for energy recovery. Jos Frijns et al. (2013) presents an installation of two centrifugal pumps upstream of a water treatment plant in Portugal. Chapallaz (2007) reports two micro-hydropower schemes with 8.3 and 21.7 kW installed in a trunk main in Morges, Switzerland. Pérez García et al. (2010) present a 25 kW micro-hydropower scheme installed in a by-pass to the pressure reduction station in the water distribution network of Murcia, Spain. A pumps operating as turbine was installed in parallel to a PRV at a water treatment plant in the UK (Williams et al., 1998).

In this paper, the potential for energy recovery in a Portuguese water trunk main system is assessed. The aim of this paper is to identify the locations were the excessive energy can be recovered by installing micro hydropower devices and to assess the economic viability of such investment. Results presented herein are part of the on-going LIFE - Smart Water Supply System (SWSS) project.

## 2 Methodology

### 2.1 Demonstration case

The demonstration case study comprises part of the drinking water transmission system that supplies the Algarve region, Portugal. It includes 13 pumping stations, 2 storage tanks and 18 delivery points to municipal water utilities (Figure 1). The system has two sources of water, namely Alcantarilha and Tavira treatment plants. Two of the pumping stations are reversible, allowing for water to flow in both directions, coming from one WTP or the other, as needed. In parts of the system, water flows by gravity. The overall water flow in the system is controlled by water levels at the municipal utilities' tanks. Because the system is located in a touristic area, water demand greatly varies through seasons and is about 5 times greater in summer than in winter. Pipe diameters range from 80 to 1200 mm and the infrastructure age is about 18 years old. In 2013, the system supplied c.a. 25.5 $Mm^3$ of water and consumed close to 5.0 GWh of electricity. For this study, gravity-fed service reservoirs were firstly identified among all existing in the system.


**Figure 1: Water transmission system scheme.**

### 2.2 Estimating hydraulic power

Flow and pressure data at the gravity fed service tanks' inlet were collected for a one-year period (2013) with one-hour time resolution. Due to seasonal variations in flow and in the tanks' filling time, the approach used consisted of estimating the energy recovery potential on a monthly basis. The available hydraulic power was calculated for each month by:

$$P_h=\gamma HQ \tag{1}$$

where $P_h$ is the hydraulic power (W), $\gamma$ is the water specific weigh (N/m$^3$), H is the available head (m) and Q is the flow-rate (m$^3$/s). An average hydraulic power value was also estimated for winter (October to April) and summer (May to September) seasons for each location. The potential energy production was calculated for each month, assuming a 75% turbine efficiency:

$$E= \eta\ P_h\Delta t \tag{2}$$

where E is the produced energy (kWh), $\eta$ is the equipment total efficiency (pump+motor) (%) and $\Delta t$ is the tank's filling time (h).

### 2.2 Estimating payback period

For the cost analysis, a few assumptions were made, namely:

(i) The efficiency of a pump as turbine is 75% and remains constant throughout the operating time, independently of the flow-rate and head variation.

(ii) Energy unit cost is constant and equal to 0.065 €/kWh.

(iii) The operational conditions in the future are identical to the ones observed in 2013 and, thus, the number of yearly hours that each tank is filling is similar.

The cost of installing the micro hydropower equipment and the necessary electric components in the existing facilities of the identified locations was calculated for two scenarios:

- Scenario A: A minimum cost of 50 k€ per PAT with less than 50 kW and 1000 €/kW for PAT with higher power.
- Scenario B: The 10th prediction curve of the cost function for pumping stations equipment reported by (Marchionni et al., 2016).

PAT's power corresponds to the maximum hydraulic power observed in each site. The payback period of the investment (PBP) was calculated at a discount rate of 2% and 6%. The Net Present Value (NPV) was calculated for a 10-year period.

## 3 Results and Discussion

### 3.1 Hydraulic power at the identified locations

Seven storage tanks fed by gravity were identified in the demonstration case and the potential for energy recovery was assessed for the seven tanks. The median head and flow for winter months (the worst scenario) and for the summer months at the tanks' inlet are plotted in Figure 2 as well as hydraulic power reference lines.

The analysis of the results indicates high seasonal variability of the available hydraulic power at the sites, located in the 5 to 100 kW range and reaching higher values in summer than in winter. The minimum hydraulic power for a feasible energy recovery project is not yet set in literature, as it depends on many variables, for example, the diurnal and seasonal flow variation, the energy cost in each country and the cost of installing a turbine or PAT for energy recovery. While a value of 30 kW is reported by (Williams et al. 1998), Gallagher et al. (2015) refers to 12.8 kW in Wales and to 22.2 kW in Ireland at tanks' inlet. Thus, for PA, PV, Q and QL tanks, where the available hydraulic power is always above 12.8 kW, installing micro hydropower turbines is likely to be feasible. However, the water flow at the tanks' inlet is not constant through time, being alternately null or close to the maximum value. Thus, despite higher hydraulic power being potentially available at some locations, particularly during the summer period, the annual energy production potential is not proportional to available hydraulic power, depending on the filling patterns of the tanks' and their seasonal variation.

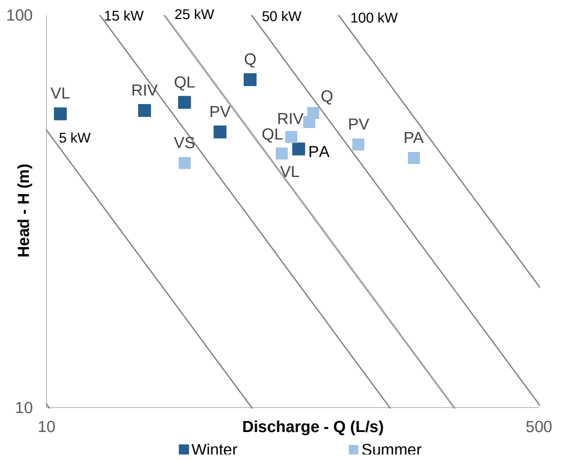


**Figure 2. Available hydraulic head and flow at the selected service tanks' inlet in winter and in summer.**

### 3.2 Economic feasibility

Results from the economic feasibility study are presented in Tables 1 and 2 for the discount rates of 6 and 2%, respectively. In each study, two cost scenarios (A and B) were assumed. The two scenario are quite similar for hydraulic powers higher than 50 kW, whereas for lower powers these costs are significantly different and the costs functions from Scenario B may not be realistic.

**Table 1. Cost analysis at discount rate of 6%**

| *Site* | *Hydraulic Power (kW)* | *Installation Cost (k€)* | | *Annual operating time (days)* | *Produced Energy per year ($10^3$ kWh)* | *Annual revenue (k€)* | *10-year NPV (k€)* | | *Payback Period (years)* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | | | | A | B | A | B |
| VS | 11.3 | 50.0 | 36.2 | 60 | 16.4 | 1.1 | -41.7 | -27.8 | - | - |
| VL | 33.1 | 50.0 | 55.0 | 40 | 32.1 | 2.1 | -33.7 | -38.7 | - | - |
| QL | 37.0 | 50.0 | 57.4 | 85 | 75.7 | 4.9 | -11.6 | -19.0 | - | - |
| Q | 51.9 | 51.9 | 65.6 | 143 | 178.3 | 11.6 | 38.5 | 24.9 | 6 | 7 |
| RIV | 53.2 | 53.2 | 66.2 | 93 | 118.6 | 7.7 | 7.0 | -6.0 | 9 | - |
| PV | 61.5 | 61.5 | 70.1 | 70 | 102.9 | 6.7 | -9.4 | -17.9 | - | - |
| PA | 88.5 | 88.5 | 80.7 | 121 | 257.2 | 16.7 | 42.0 | 49.7 | 7 | 6 |

**Table 2. Cost analysis at discount rate of 2%**

| *Site* | *Hydraulic Power (kW)* | *Installation Cost (k€)* | | *Annual operating time (days)* | *Produced Energy per year ($10^3$ kWh)* | *Annual revenue (k€)* | *10-year NPV (k€)* | | *Payback Period (years)* | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | A | B | | | | A | B | A | B |
| VS | 11.3 | 50.0 | 36.2 | 60 | 16.4 | 1.1 | -40.2 | -26.4 | - | - |
| VL | 33.1 | 50.0 | 55.0 | 40 | 32.1 | 2.1 | -30.9 | -35.9 | - | - |
| QL | 37.0 | 50.0 | 57.4 | 85 | 75.7 | 4.9 | -4.9 | -12.3 | - | - |
| Q | 51.9 | 51.9 | 65.6 | 143 | 178.3 | 11.6 | 54.3 | 40.6 | 5 | 6 |
| RIV | 53.2 | 53.2 | 66.2 | 93 | 118.6 | 7.7 | 17.4 | 4.4 | 8 | 10 |
| PV | 61.5 | 61.5 | 70.1 | 70 | 102.9 | 6.7 | -272 | -8.8 | - | - |
| PA | 88.5 | 88.5 | 80.7 | 121 | 257.2 | 16.7 | 64.7 | 72.4 | 6 | 6 |

Net present values were estimated for a 10 year-time frame. Only projects of positive 10-year NPV were considered to be feasible. Hence, only three sites are potential locations for installing PAT, namely Q, RIV and PA. These results are not in accordance with the previous results, which indicated four sites (Q, QL, PV and PA). While Q and PA are common to both approaches, RIV, QL and PV are not. These results show that potential energy recovery assessment cannot be based only on the available hydraulic power, but that it has additionally to take into account other factors, such as, the operating time of the system throughout the year and the variable PAT efficiency with the operating point. In Figure 3, each tanks' filling time are plotted against maximum available hydraulic power.

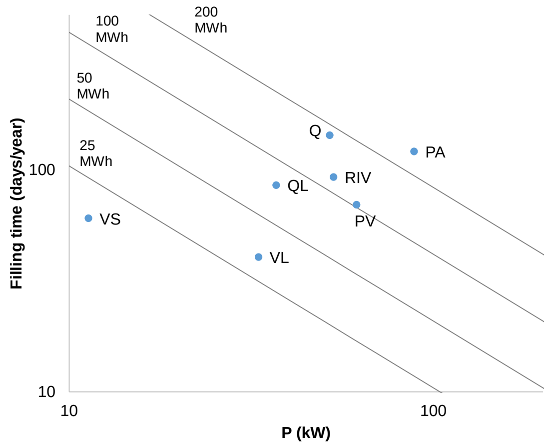


**Figure 3. Tank's filling time at the maximum power and produced energy reference lines.**

Results show that the three viable solutions have hydraulic powers higher than 50 kW simultaneously with operating times approximately higher than 100 days per year. One of the potential sites according to the available hydraulic power (PV) is not a viable solution due to the reduced operating time (70 days). Reference curves for the annual energy produced are also plotted, showing that the viable cases have a produced energy higher than 100 MWh per year.

The use of the two cost functions did not lead to much different results, as the viable projects are the same, except for RIV, and the payback periods are similar. The sensitivity analysis shows that the use of a lower discount rate value tends to decrease the payback period. For RIV project, the use of 2 % turns this case as a viable solution for both cost scenarios. These results show that economic feasibility of the micro hydropower solution additionally depends on the criteria chosen in the cost analysis. While being apparently viable, recover the investment of a PAT solution in RIV tank inlet will take much more time than at the other two sites. Hence, Q and PA are the locations where PAT should be installed and where energy can be recovered in the demonstration case.

## 4. Conclusions

In this study, an assessment of the energy recovery potential of a Portuguese water transmission system is presented. The paper shows that the installation of pumps operating as turbines is feasible in two sites in the system, located at the inlet of two storage tanks fed by gravity. In addition, it shows that in feasible projects the available hydraulic power is higher than 50 kW and simultaneously the tanks' filling time is higher than 100 days/year.

The cost of installing a PAT can be recovered after 5 to 7 years, depending on the cost functions used to estimate the investment and on the discount rate assumed in the economic feasibility study. The impact of such factors on potential energy recovery assessment projects feasibility must be further studied.


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