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Feasibility assessment of micro-hydropower for energy recovery in the water supply network of the city of Fribourg

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ABSTRACT: In water supply systems there is potential for hydropower production at several scales, from small hydro to micro. The energy recovery within the urban water supply networks is a type of micro-hydro that may be useful for the control of excessive pressures. On the other hand, local decentralized production of electricity may have multiple uses, considering self-consumption at local grid level or storage. However, there is still a lack of technologies and specific solutions for such applications, since the flows are highly variable and the available heads are small and limited to service pressures. A scheme specially conceived for water supply networks making use of a micro turbine is proposed. Adequate positioning conditions are identified using a search algorithm which considers both the assessment of the energy production and sizing of the main equipment and works. Typical schemes are proposed where the installation of up to four turbines is possible within the same buried chamber created around an existing pipe. Preliminary results obtained for a network case study show that the implementation of the proposed energy recovery solution is feasible. The installation of a by-pass revealed to have a key role in the feasibility of each solution, demanding customized engineering judgment. Further testing of the search algorithm as well as a first in-situ implementation of the scheme may be foreseen in the near future.

1 INTRODUCTION

The present concerns with environment and energy efficiency contribute for a growing new interest on small and even micro-hydropower. These small scale technologies, micro-hydro designating productions below 100 kW of installed power (Ramos et al. 2009), allow a decentralized supply for local demand, which has the advantage of reducing transmission losses (Weijermars et al. 2012).

One of the most promising applications of micro-hydropower lies within water supply systems (WSS). These are systems which are pressurized and where the pressure control is important to avoid water losses and pipe damage (Carravetta et al. 2012, Xu et al. 2014). The use of turbines instead of pressure reduction valves (PRV) for the excess pressure dissipation allows to recover part of this energy (Ramos et al. 2010, McNabola et al. 2014, Su and Karney 2015). Also, the implementation in existing water supply infrastructure has the advantage of smaller costs (Sitzenfrei and von Leon J 2014).

Although many studies exist in literature on pressure control in urban water systems, there is still a lack of technologies and specific solutions for energy recovery in these conditions. Carravetta et al. 2012 proposed the use of pumps as turbines (PAT) between district metered areas and Corcoran et al. 2015 studied the use of PAT, Francis and Kaplan turbines.

In the present work, a feasibility study is carried for the installation of micro-turbines within the urban areas of the WSSs. An arrangement is defined, with inline tubular propellers installed within existing pipes of the network, and the main quantities are estimated in order to have an economic analysis.

The ideal location of such an arrangements in a water supply network depends on numerous factors: the flow rates, which in a urban system are highly variable along the day; the available head, since the micro-hydro operation should not affect the quality of the service to the population and thus minimum service pressure ought to be guaranteed; and the geometry of the network, due to the distribution of the flow within closed meshes of a network.

To identify the optimal placement of the turbines, an algorithm was developed to optimize the economic value. This algorithm, coupled with a hydraulic solver, is an upgraded version of a previously developed work

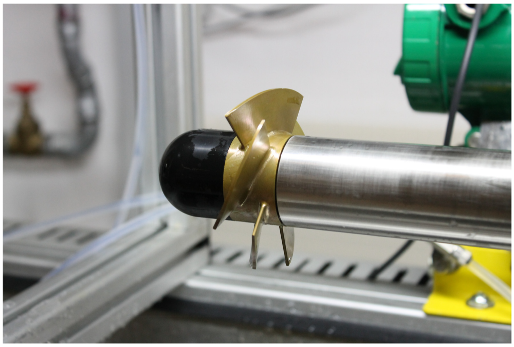

Figure 1. Model of the runner of the 5BTP, with 85 mm of diameter.

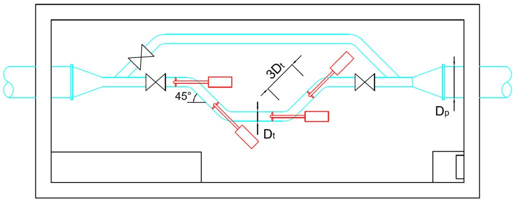

Figure 2. Schematic lay-out of a chamber equipped with four turbines.

based on the Simulated Annealing strategy (Samora et al. 2016).

The city of Fribourg, Switzerland, was used as a case study to obtain estimations on the energy produced with the proposed arrangement and of its economic value.

2 MICRO-HYDROPOWER SCHEME

The five blade tubular propeller (5BTP) is appropriate for energy recovery in water supply systems since its operation is based on variable flow rates and low heads. This turbine was first developed at Instituto Superior Técnico, Portugal and recently it has been subject to experimental tests in Switzerland, in a cooperation between the École Polytechnique Fédérale de Lausanne and the University of Applied Sciences and Arts of Western Switzerland.

The turbine, as shown in Figure 1, consists of a runner with five fixed blades attached to a bulb upstream and to an axis downstream. The axis connects to an external generator, leaving the pipe through a 45° curve.

For the placement of this turbine within a water supply system, the configuration shown in Figure 2 is proposed. This scheme is based on the construction of a buried concrete chamber around an existing pipe where the installation of up to four turbines is possible.

The diameter of the runner D_t is always inferior to the diameter of the existing pipe D_p.

The electromechanical groups are composed by the turbine, the generator and a frequency converter that controls the rotational speed according to flow measurements.

For construction and maintenance, access to the equipment is required and therefore the isolation of the chamber from the network is an aspect to take into account. As most WSN are composed of meshes, there is often redundancy in the supply and valves are in place to isolate branches. Nevertheless, if we consider a node fed with no redundancy, a bypass must be created and the hydraulic circuit adapted. The creation of such bypass needs the installation of three maintenance valves, that can be placed in D_t sections.

3 METHODOLOGY AND CASE STUDY

3.1 *Search algorithm*

Water supply networks are complex systems, with variable flows, redundancy of supply and pressure restrictions. Hence, the decision of the placement of the turbines within a network needs a deep analysis of all factors involved. To perform this analysis, a search algorithm which is based on previous works (Samora et al. 2016) was used. In this algorithm, a simulated annealing process was developed to locate the placement of turbines in a network that maximize the energy production.

In this work, the algorithm was modified to allow up to four turbines in the same branch of the network and the cost function was changed to:

$$f(X) = {}^{1}\!\!\diagup_{NPV_{20\,years}} \tag{1}$$

where $X = (x_1, \dots, x_n)$ is the solution vector, representing the placement of N_t turbines, in this particular case $N_t = 4$, and $NPV_{20years}$ is the net present value resulting from the sum of the cash-flows over 20 year of operation.

Only investment costs (IC) were considered and it was assumed they would take place in the year prior to commissioning. Hence, the net present value after 20 years of operation is given by the following discounted cash flow model:

$$NPV_{20\,years} = \left(\sum_{i=1}^{20} \frac{E_{annual} * t}{(1+r)^{i}} \right) - IC \tag{2}$$

where E_{annual} is the annual energy production with the solution X, t is the selling energy tariff and r is the discount rate. The annual energy production is given by

$$E_{annual}(X) = \rho g \sum^{T} \Delta t \sum_{n=1}^{Nt} \eta_n Q_n H_n \tag{2}$$

where g is gravitational acceleration (m/s^2), ρ is the water density (kg/m^3), T corresponds to the time window of one year with an hourly time step Δt and, for each n turbine, Q_n (m^3/s) is the flow discharge, H_n (m)

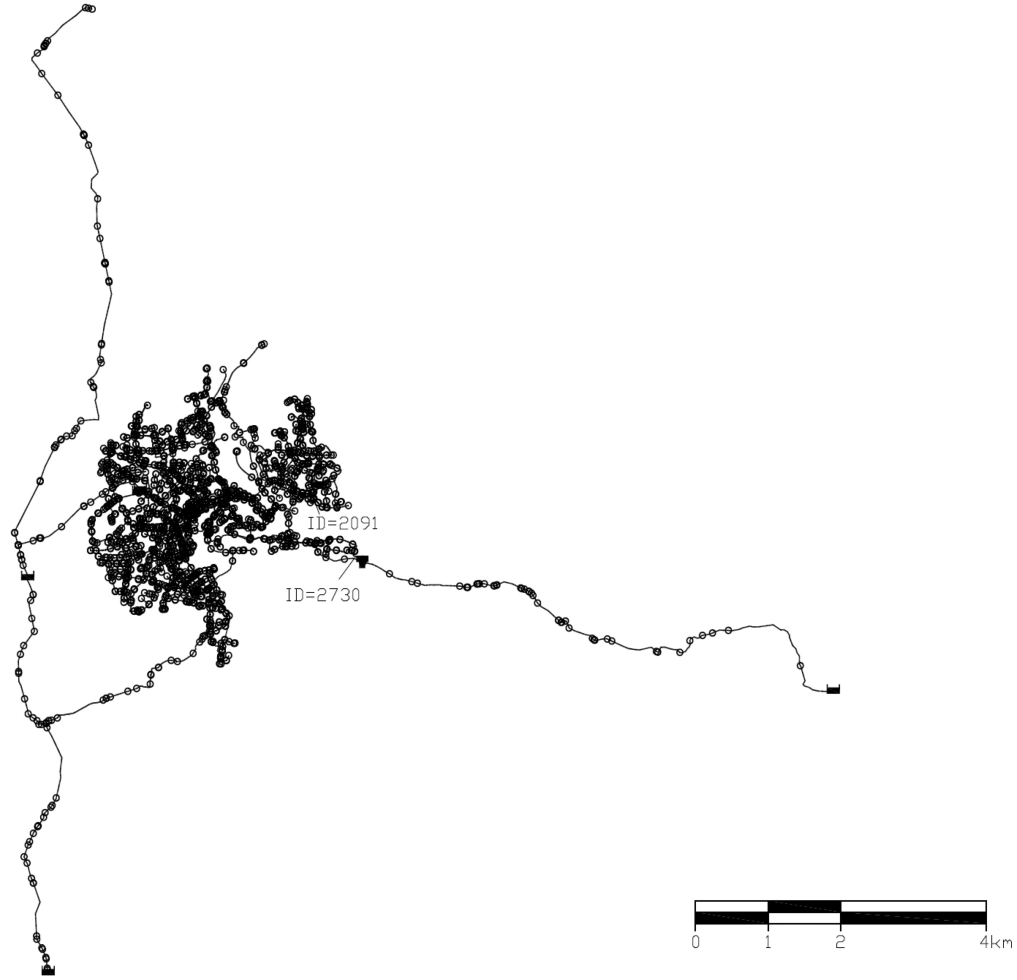

Figure 3. Network of the water supply system of Fribourg, Switzerland, used as case study.

is the net head in the turbine and η_n is the total efficiency. The total efficiency is given by the turbine and generator efficiencies. The first depends on the efficiency curve of the turbine, which wasstudied and the second was considered constant and equal to 85%.

3.2 *Case study*

The search algorithm was applied to the drinking water supply network of the city of Fribourg, Switzerland. The model, with 2972 links, 2805 nodes, 15 PRV and 7 water tanks was provided by the Industrial Services of Fribourg (Figure 3). The network has a total of 216 m of elevation difference and 130 l/s of average daily consumption over 24 h. A minimum pressure restriction of 30 m was assumed, taking into account the typical height of buildings in Switzerland and the need to supply with enough pressure to the consumers.

Based on real data and on the model implemented by the network managers, an average consumption of 0.108 l/s was associated to each demanding node and a typical pattern of hourly variation along the day was applied.

To estimate the revenues, the electricity sell price adopted was the current feed-in-tariff in Switzerland of 0.33 CHF/kWh for this type of power plant (SFC 1998, SFOE 2015). Discount rates of 4%, 6% and 8% were considered in this study.

Finally, to estimate the investment costs, the main quantities of the power plant presented in Figure 2 were estimated in relation to the pipe and turbine diameters and installed power. The elements considered were: stainless steel, concrete, excavation, earth fill, electromechanical equipment, isolation valves, flowmeters. Unit prices, presented in Table 1 were associated to these quantities.

The installation of isolation valves is dependent on the existence of redundancy to the nodes of the target branch. However, since the need for a bypass is restricted to short periods of time, it was considered that the minimum pressure during construction and maintenance is 15 m.

Table 1. Unit prices.

Element	Unit price
Stainless steel	7 CHF/kg
Reinforced concrete	250 CHF/m^3
Excavation	30 CHF/m^3
Earth fill	20 CHF/m^3
Electromechanical equipment	1 CHF/W
Maintenance valve w/ wheel drive	190 000 CHF/m^2
Flowmeter	550 CHF/unit

Table 2. Results for the installation of four turbines.

		NPV$_{20years}$ (kCHF)		
X	E (MWh/year)	r: 4%	6%	8%
(2730, 2730)	121	513	428	362
(2730, 2730, 2730)	128	546	456	386
(2091, 2730, 2730, 2730)	144	573	473	396

4 RESULTS

The search algorithm was run for the installation of two, three and four turbines in the case study network. The produced energy and the net present value after 20 years of are presented in Table 2 for the obtained solutions.

Pipe 2730 (identified in Figure 3) has a clear superior potential for hydropower production. In Table 2, all the solutions for the position of turbines imply the use the same pipe except for four turbines. A turbine imposes a head loss that constrains the passage of flow and, even though the solution with four turbines implies the construction of two chambers, the effect of the limitation of flow discharge with four turbines in pipe 2730 does not seem to compensate. No particular limit to this reduction was imposed in this case, as it was assumed constant levels in all reservoirs and tanks and continuous consumption in the nodes.

To illustrate the comparison between costs and energy production, in Figure 4 are presented the breakdown of costs for these three solutions and also of the solution where all four turbines placed are in pipe 2730. The diameter of the runner in each solution is dependent on the maximum flow in the pipe, and so it is not the same in all cases.

It can be seen from Figure 4 that no maintenance valves are present in the breakdown of investment costs for any of the solutions. Therefore, these position in the network have redundancy in the supply, not requiring the constructions of a by-pass. In fact, pipe 2730 is located in one of the main paths connecting an external tank to the city. This path is the region of the network with the highest flow rates and the pressures are high. Also, a PRV is already in service in this path. Nevertheless, despite the importance of this path, the city possesses other water sources. Since the closure of these pipes did not induce a pressure below 15 m, a by-pass was not considered necessary.

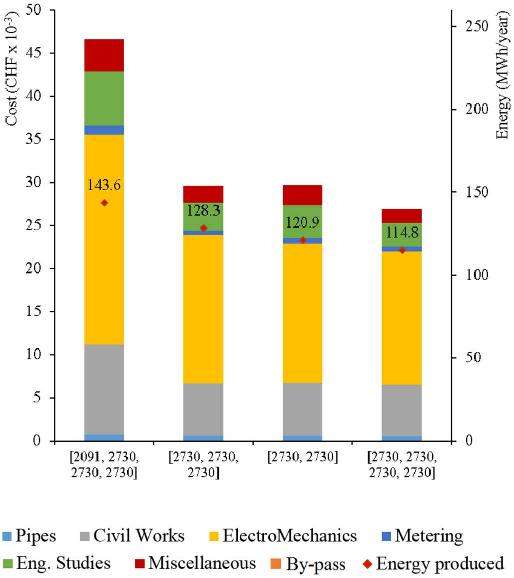

Figure 4. Breakdown of investment costs and energy produced for solutions with four turbines.

However, if a by-pass would be required in all chambers, the maintenance valves would represent 20–30% of the total IC, according to the unit prices assumed. In Figure 5 the NPV and the total IC for these solutions with and without the construction of a by-pass are presented. According to this figure, the solutions with the installation of valves would still be feasible and the order of best solutions remains untouched. Nevertheless, this is an aspect to take into account when studying micro-hydropower installations in urban water supply systems.

As it has been mentioned before, the pipe with higher potential, used in all proposed solutions, is located in one of the main paths of water supply to the city. The inclusion of turbines would have a direct impact on the flow discharge in this axis, which is not limiting in this model due to the redundancy that the existence of other sources give. Nevertheless, there are multiple PRV along this path, and an actual solution would be to replace them by multiple turbines.

5 CONCLUSIONS

This work presents a feasibility study of the installation of micro-turbines in the urban water supply network of the city Fribourg, Switzerland.

A possible hydropower arrangement based on a new and recently tested turbine, the 5BTP, is proposed. The best location for buried chambers, built around the existent pipe, with up to four turbines installed, is analyzed considering the net present value after 20 years

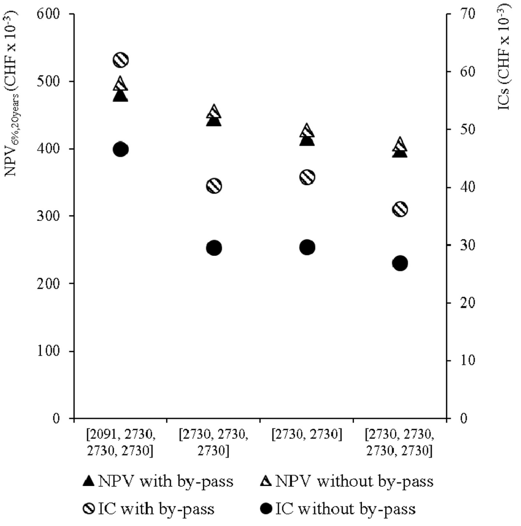

Figure 5. NPV$_{20years}$ with 6% of discount rate and IC, with and without the installation of maintenance valves.

of operation (NPV$_{20years}$). For this purpose, an optimization algorithm based on the simulated annealing strategy was used.

It can be concluded that, for the unit prices and sell tariffs assumed, the arrangement is economically feasible for the installation of four turbines.

The installation was tested for two to four turbines. It came to no surprise that the main pipe chosen in all solutions belong to the path with the highest discharge flows and where there were already PRV installed. However, the best configuration for four turbines imply placing the turbines in multiple pipes. It was concluded that the reduction of the flow discharge due to the insertion of a first chamber and corresponding head-loss justified the interest of building a second chamber.

Finally, the effect of the installation of a by-pass for construction and maintenance was analyzed. The by-pass has an important weight in the investment, representing 30% of the total cost. The pertinence of paying this premium to guarantee continuous operation will have to be assess on a case by case basis, since it is quite depending on site conditions, on the duration of interruption and on each utility's procurement strategy.

In future work, further testing of the search algorithm in other geometries and in networks with different utilities would contribute to better characterize the potential for this type of energy recovery. Also an in-situ implementation of the 5BTP would allow for a proof-of-concept validation of the methodology, as well as allow for troubleshooting of eventual practical issues.

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