Energy Recovery in Water Networks: Numerical Decision Support Tool for Optimal Site and Selection of Micro Turbines

Bernardete Coelho[1] and António Andrade-Campos[2]

Abstract: Energy efficiency plays a large role in the sustainability effort of water utilities. In gravity-fed pipe networks that present excessive pressures, the installation of micro turbines or pumps-as-turbines for energy recovery can provide significant benefits. The main obstacles associated with this kind of solution include the high cost of implementation (equipment and installation) and the time-consuming task of searching for potential and feasible sites for the power plant implementation. In this work, a numerical methodology for the analysis of any water supply and distribution network in order to optimally locate sites for maximum energy recovery and to preliminarily select or design turbines is proposed and validated with a case study. The idea of this decision support tool is to facilitate the assessment of the potential for energy production in networks and encourage the implementation of this type of efficiency measure. The proposed approach consists of two main stages: (1) identification of potential sites for energy recovery through an optimization procedure and (2) selection of adequate types of turbine and preliminary feasibility analysis. **DOI: 10.1061/(ASCE)WR.1943-5452.0000894.**

Author keywords: Energy recovery; EPANET; Micro hydro turbines; Site location; Turbine selection; Water supply and distribution.

Introduction

Energy efficiency plays a large role in the sustainability effort of water utilities (Hamiche et al. 2016). Globally, energy accounts for 35% of the total expenses associated with water production (Black & Veatch 2015). Furthermore, sustainability and financial concerns intensify with increases in energy prices (Kernan et al. 2017).

Renewable energy sources can be used as a response to the large energy demand in the water and waste water sector, diminishing the consumption of fossil fuels and hence reducing carbon emissions (Coelho and Andrade-Campos 2014). Because growth in renewable energy is recognized as one of the principal drivers of change in the smart energy market (ARUP 2013; SENSUS 2012), a similar approach could also be followed to foster adoption in the water market. Additionally, the applications of intermittent solar or wind renewable sources in water networks may benefit from the storage capacity of these specific networks. It is possible to use the intermittent available energy, which affects the stability and reliability of electricity networks, to pump the water to storage tanks for later distribution by gravity.

When the subject is water, hydro power generation is probably the first renewable energy solution that arises. In fact, a topic that has received particular attention in the last years is related to energy recovery in water supply systems (WSSs), particularly the recovery of excessive pressure energy in the networks using turbines (or pumps-as-turbines). However, the identification of reliable locations for the installation of hydro turbines in the networks is not easy because of the large dimensions and complexity of the pipe networks and also the high variability typically associated with the operation of such systems, which also makes this initial planning stage very time consuming. In fact, the use of hydraulic turbines inserted directly in distribution networks is considered one of the most complex forms of hydraulic energy recovery in WSSs (Vilanova and Balestieri 2014). On the contrary, significant opportunities for energy recovery can be identified in places with equipment such as control valves or pressure-reducing valves for pressure management (PM) in the networks. Given the large benefits of PM in WSSs, such as leakage reduction, decrease of pipe burst occurrences, and water consumption reduction (Vicente et al. 2015), the number of related studies has grown significantly. Vicente et al. (2015) provided a comprehensive analysis of the most innovative issues related to PM in the last decade. The most recent works on this topic have essentially covered the problems of optimal valve location or setting (Ali 2014; Fontana et al. 2016; Paola et al. 2016, 2017), as well as valve real-time control (Berardi et al. 2015; Fontana et al. 2016; Campisano et al. 2016), where the objectives usually consist of pressure minimization or leakage reduction.

Because the pumps available in the market are more adequate for reduced power and flows than turbines and, at the same time, represent lower investment costs, these present advantages for their use in micro hydroelectric plants (5 to 100 kW) either as pumps or turbines (Gonçalves and Ramos 2008). Furthermore, according to Ramos et al. (2010), it is possible to use pumps-as-turbines (PATs) with relatively higher efficiency (up to 85%). The main disadvantage is the high PAT dependency on the flow rate, which does not allow medium and high variations of flow (Caxaria et al. 2011).

In order to efficiently couple pressure management and energy production in water distribution networks (WDNs), Fontana et al. (2016) developed a laboratory prototype of a network containing a PAT and regulating valves (flow and pressure). A feedback

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control methodology for the automatic real-time control of the valve settings was implemented and allowed to properly regulate the pressure in the network and, at the same time, regulate the flow through the PAT for energy maximization. This methodology resulted in good PAT efficiency.

The majority of the studies addressing the topic of energy production in water networks have analyzed the feasibility of using PATs compared to other solutions (Lopes and Martinez 2006; Caxaria et al. 2011; Fontana et al. 2012; Carravetta et al. 2012; Giugni et al. 2014). The study of Lopes and Martinez (2006) demonstrated that the use of PATs can represent a viable choice, especially for installations of less than to 4 kW. The works of Fontana et al. (2012) and Giugni et al. (2014) analyzed the use of PATs instead of pressure-reducing valves (PRVs) for loss reduction and energy production in WSSs. Fontana et al.'s (2012) methodology, based on the use of a simulator and a genetic algorithm (GA) for the optimal location of PRVs, was applied to a case study in Naples (Italy). The results demonstrated that the optimal location for water loss reduction does not maximize energy production. However, a relatively large amount of energy can be recovered with a significant reduction in water losses. Carravetta et al. (2012) proposed a PAT design method based on a variable operating strategy for the identification of the PAT performance curve that maximizes the produced energy for a certain flow and pressure head distribution pattern. The authors pointed out two main problems related to the design of small hydro power plants: (1) the lack of a complete series of characteristic curves of industrial PATs and (2) the need for a strategy for turbine selection.

Brady et al. (2016) worked on the impact of flow and head variations on turbine efficiency. From the three analyzed scenarios (a Kaplan turbine, a single PAT, and two different-sized parallel PATs), using 20 years of flow and head real data from three PRVs, Brady et al. (2016) concluded that significant power generation capacity existed across each of the scenarios. The Kaplan turbine presented the highest energy production because of its higher overall efficiency. However, it also costs 25% more to install than the single PAT or the two-PAT system. In terms of payback periods, the Kaplan turbine was demonstrated to be the best choice because of shorter periods. At the same time, the two-PAT system presented shorter payback periods than the single PAT, differing from the Kaplan for only 1 year.

As demonstrated by the literature, studies related to energy production in water networks tend to be limited to the use of pumps-as-turbines while not exploring the advantages of the use of turbines. The increasing number of micro hydro turbines in the market as well as their overall higher efficiencies, noninterference with normal pipe flow, and lower payback periods are typically the main advantages that can be associated with turbines when compared with PATs. In this work, a numerical tool capable of identifying the potential of distinct types of turbines for energy production in any type of water network is presented. The developed tool performs, in its first stage, the identification of the locations in a network with the highest potential for energy recovery using an optimization procedure. In the post-optimization stage, the most adequate types of turbine for each site location are determined and a preliminary technical and financial feasibility analysis for each case is provided.

Conditions for Hydro Power Generation

According to the principle of energy conservation, also known as the Bernoulli equation (Walski et al. 2003), the energy balance of a steady flow from A to B will obey the following relationship (Ramos et al. 2000):

$$Z_A + \frac{P_A}{\gamma} + \frac{v_A^2}{2g} = Z_B + \frac{P_B}{\gamma} + \frac{v_B^2}{2g} + \Delta H_{AB} \qquad (1)$$

where ΔH_{AB} corresponds to the head loss between A and B and is equal to the difference between the total heads at A, H_{A}, and at B, H_{B}. This available head difference ($H_{\mathrm{A}} - H_{\mathrm{B}}$), also called the gross head H_{gross}, can be converted into mechanical and electrical energy using a turbine or a PAT. The final useful head or net head H_{net} is smaller than the gross head and depends on the turbo-machinery efficiency, accordingly

$$H_{\mathrm{net}} = \eta_{\mathrm{turb}}\eta_{\mathrm{transf}}\eta_{\mathrm{gen}}\eta_{\mathrm{gear}}H_{\mathrm{gross}} = \eta_{\mathrm{t}}H_{\mathrm{gross}} \qquad (2)$$

where η_{turb}, η_{transf}, η_{gen}, and η_{gear} = the turbine (or PAT), transformer, generator, and gearbox efficiency, respectively.

Adequate head and flow are necessary requirements for hydro power generation. Once a flow rate and head have been estimated, the capacity of a hydro power plant can be estimated by

$$P_{\mathrm{net}} = \gamma Q_{\mathrm{d}} H_{\mathrm{d}} \eta_{\mathrm{t}} = P_{\mathrm{gross}} \eta_{\mathrm{t}} \qquad (3)$$

where P_{net} represents the power to be installed, $\gamma = \rho g$, where ρ = the density of the water and g = the gravitational acceleration; Q_{d} = the turbine design flow; H_{d} = the turbine design or gross head; η_{t} = the efficiency of the set turbine, generator, transformer, and gearbox, if applicable; and $P_{\mathrm{gross}} = \gamma Q_{\mathrm{d}} H_{\mathrm{d}}$ corresponds to the gross power. Efficiency can be evaluated only after the plant configuration and the selection of the turbine (Colorado Energy Office 2015).

Because the potentially recoverable power is dependent on the available flow and head ranges, the determination of such ranges in each pipe of the network should be the first step for the identification of potential sites for energy recovery. However, in water networks, the value of the head drop (gross head) in each location can be variable because of the variation of water levels in reservoirs or tanks as well as the head losses between such reservoirs or tanks and each location. An average value of the head can be considered the design head for a preliminary assessment.

For the estimation of the flow conditions in potential sites, the representation of flow-duration curves (FDCs) is a common practice (Natural Resources Canada 2005; European Small Hydropower Association 2004a). Although for hydro power generation in streams, daily flow data recorded for a number of years is typically used, in the case of water networks, because of the fairly repetitive flow patterns, hourly data (for a day or days) should be sufficient in a preliminary analysis. The FDC enables the assessment of flow variability at a particular site and the determination of an initial design flow for the hydro power scheme. The Colorado Energy Office (2015) recommended an initial estimation of the design flow for a small hydro system equal to a flow presenting an exceedance probability between 30 and 60%. Multiple turbines can be combined to achieve the desired design flow, providing a certain flexibility.

After determining the design flow Q_{d} and design head H_{d} for a specific site, an approximation of the potentially recoverable power P_{gross} can then be computed using Eq. (3). The net recoverable power P_{net} is smaller than the available gross power because it depends on the selected turbine and the associated efficiency of the set turbine-generator (and other equipment, if applicable) η_{t}.

The identification of the most adequate site for the development of a hydro power scheme in a water network is commonly treated as an optimization problem whose main objective is the maximization of energy production (power generation) or the minimization of the pressures in the network in order to reduce water leakages (Corcoran et al. 2015; Fecarotta et al. 2015; Fontana et al. 2012, 2016; Giugni et al. 2014). In fact, both objectives are interconnected. In any case, a pressure constraint related to limitations of pressure often imposed by the regulator for security and comfort reasons (Samora et al. 2015) should always be considered.

Optimal Site Location Approach

Modeling a PRV in specific locations of a network, obtaining the flow rate and the head drop through the valve during the simulation period, allows computing the energy that is dissipated in such equipment and, consequently, the potentially recoverable energy. In *EPANET* (Rossman 2000), the head drop through a PRV is computed by the equation of the minor head losses through the link, which can be written in terms of the flow rate Q and the valve or link diameter D

$$h_{\mathrm{m}} = K_{\mathrm{m}} \frac{8}{\pi^2 g} \left(\frac{Q}{D^2} \right)^2 \tag{4}$$

where the minor loss coefficient K_{m} is the parameter that can be adjusted by the user in order to maximize the head drop and thus maximize the potentially recoverable power.

Similar to the approach proposed by Giugni et al. (2014), in this work, the determination of optimal locations for a turbine installation is performed using an optimization approach to find the best locations of PRV (and the associated minor loss coefficient) in order to maximize the potentially recoverable energy. Such an optimization problem can be mathematically described as

$$\begin{aligned} &\underset{K_{\mathrm{m}}}{\text{maximize}} \quad E_{\mathrm{recov}} = \gamma \sum_t Q_t \times [h_{\mathrm{m},t}(K_{\mathrm{m}})] \times t_{\mathrm{step}}, \\ &\quad t = 1, \ldots, n_{\mathrm{steps}} \\ &\text{subject to} \quad P_{i,t} - P_{\min} \geq 0, \quad i = 1, \ldots, n_{\mathrm{dnodes}} \end{aligned} \tag{5}$$

where t_{step} = the duration of the time-step; n_{dnodes} = the number of demand nodes; $P_{\min}$ = the minimum pressure required in the demand nodes; and $P_{i,t}$ = the pressure at node i in the time-step t. In this optimization problem, the decision variable is the minor loss coefficient K_{m}, which can take values according to the valve opening.

The idea is to test distinct scenarios in a network modeled with *EPANET* by automatically installing a PRV in each existent pipe at a time (one different scenario for each tested pipe) and determine the valve's minor loss coefficient that maximizes the potentially recoverable energy E_{recov}. A simple line search strategy is used to solve the presented optimization problem. In this method, the search starts at an arbitrary point x_0; then, a certain step size λ_k determines how far this initial solution should move along a certain direction d_j until finding the optimum (maximum, in this case). Using a line search strategy, any new solution K_{m}^{j+1} can be found according to

$$K_{\mathrm{m}}^{j+1} = K_{\mathrm{m}}^{j} + \lambda^j d^j \tag{6}$$

In this work, similarly to the well-known steepest descent method and knowing that $\frac{\partial E_{\mathrm{recov}}/\partial K_{\mathrm{m}}}{\|\partial E_{\mathrm{recov}}/\partial K_{\mathrm{m}}\|} = 1 \geq 0$, a fixed value of the search direction $d^j = 1$ is used for all k^{th} iterations. The initial solution considered is $K_{\mathrm{m}}^0 = 0$, which corresponds to a fully open valve. The optimal solution can be found using fixed step-sizes λ^j. In each iteration, the objective function E_{recov} and the constraint functions are evaluated by running *EPANET*. For a nonlinear E_{recov} function, a finite differences approximation can be considered to obtain the function gradient. The iterative process stops when an active constraint is activated.

Preliminary Turbines Selection and Design Approach

The development of a cost-effective and efficient small-scale hydro power project implies the optimal selection and design of the hydro turbine(s) (Sangal et al. 2013). In small-scale hydro applications, the turbines used are scaled-down versions of the conventional large hydro turbines (Natural Resources Canada 2005). Generally, a turbine can be classified according to the principles of operation as: (1) impulse turbines (Pelton, cross-flow, and Turgo turbines) or (2) reaction turbines (Francis, Kaplan/propeller, and pumps-as-turbines).

The optimal selection and design of a turbine should take into account both technical parameters, such as the specific speed, diameter, and efficiency of the turbine, and financial parameters, such as the costs of equipment, installation, civil works, and so on. Both the technical and financial viability of each potential small-scale hydro power project are very site specific (Natural Resources Canada 2005).

In this work, the methods presented to select and design turbines and evaluate the corresponding technical and financial feasibility are essentially based on the approaches suggested by the Natural Resources Canada (2005), also applied in the *RETScreen* software.

Technical Feasibility

In technical terms, the selection of the turbine should be based on its suitability to the site's available head and flow. The head range should be the first criterion to take into account in the turbine's selection; however, more than one type of turbine can be used for some head ranges. The operation head ranges for each main type of turbine can be seen, for example, in European Small Hydropower Association (2004b).

In the process of selection of a turbine, the associated efficiency of the turbo machine also presents an important role because the net recovered energy depends on such a parameter. Turbines that present high efficiencies under broad ranges of flow are adequate for schemes developed in water networks because of their high variability of flow. However, turbines capable of covering a large operating range are also typically more expensive (Colorado Energy Office 2015).

The turbine's efficiency curves take into account a number of factors, including the rated head, the runner diameter and the turbine-specific speed. In this work, the determination of each turbine's efficiency, based on its specific speed (if applicable) and runner diameter, which are also design parameters, is performed using the equations proposed by Natural Resources Canada (2005). Such equations, presented in Table 1, were derived from a large number of manufacturer efficiency curves for different turbine types and head and flow conditions.

Because the flow rate in water supply and distribution systems is usually highly variable, the turbine's efficiency, and hence the recoverable power, will be also largely variable.

Financial Feasibility

The idea of a financial feasibility analysis is to determine whether the balance of costs and savings of a certain project is attractive. The financial analysis model proposed by Natural Resources Canada (2005) uses formulae based on standard financial terminology that can be found in most financial textbooks. The model considers year 0 as the initial investment year and the occurrence of cash flows at the end of the year. According to this model, a complete financial feasibility study includes a large number of contributors for the initial costs of a small-scale hydropower project,

Table 1. Results for the Pipes of the Napoli Est Network That Presented the Highest Hydraulic Energy, S1 to S8, and for the Pipes Considered in the Scenarios Presented by Fontana et al. (2012), A, B, and D

Scenarios	Pipe ID	Flow range (l/s)	Head drop range (m)	Daily hydraulic energy (kWh/day)
S1	P325	28–124	5.433–13.637	29.47
S2	P262	6–44	3.651–12.773	10.47
S3	P354	239–339	0.062–0.120	10.16
S4	P29	9–13	1.091–2.267	7.66
S5	P266	8–13	7.892–19.666	6.64
S6	P358	9–26	0.077–0.144	6.12
S7	P261	8–16	3.594–12.572	5.55
S8	1	240–339	0.031–0.059	5.04
A	1	240–339	0.031–0.059	5.04
B	P151	143–204	0.044–0.086	4.42
	P200	62–86	0.009–0.018	0.38
D	P111	67–89	0.014–0.025	0.55
	P134	62–87	0.071–0.136	2.96
	P354	239–339	0.062–0.120	10.16
	P358	9–26	0.077–0.144	6.12

such as (1) development, (2) engineering, (3) energy equipment and installation, (4) access road, (5) transmission line, (6) transformer and installation, (7) civil works, (8) penstock and installation, (9) canal, and (10) others (miscellaneous). In this work, a preliminary (simplified) financial analysis is proposed by including the following factors: engineering C_{eng}, energy equipment and installation C_{equip}, and civil works C_{civ}. Considering that $C_{\text{equip}} = C_{\text{gen}} + C_{\text{t}} + C_{\text{inst}}$, where C_{gen} corresponds to the generator and control costs, C_{t} represents the turbine and governor costs, and C_{inst} the costs of energy equipment installation, then the total investment C_{inv} can then be obtained by

$$C_{\text{inv}} = C_{\text{eng}} + C_{\text{gen}} + C_{\text{t}} + C_{\text{inst}} + C_{\text{civ}} \tag{7}$$

The equations used to compute C_{eng}, C_{gen}, C_{t}, C_{inst}, and C_{civ} are provided in Table 1 and are written in terms of the design head and flow of the site.

After calculating the total investment cost for the project development, the annual income from the energy production C_{EP} should be estimated by means of the expected annual recovered energy E_{recov} and the sale price of energy C_{energy} (*i.e.* $C_{\text{EP}} = E_{\text{recov}} \times C_{\text{energy}}$). It should be noticed that the sale price of energy as well as the existence of possible incentives are country-dependent factors and can be determinant in the feasibility of the project.

To determine the return on investment, a cash-flow analysis on an annual basis can be performed (Natural Resources Canada 2005). The simple payback (SP) is computed by

$$\text{SP} = \frac{C_{\text{inv}} - \text{IG}}{C_{\text{in}} - C_{\text{out}}} \tag{8}$$

where C_{inv} corresponds to the investment cost (total initial cost of the project); IG refers to eventual incentives and grants; $C_{\text{in}} = C_{\text{EP}}(1 + r_{\text{e}})$ = the annual cash inflow; and $C_{\text{out}} = C_{\text{OM}}(1 + r_{\text{i}})$ = the annual cash outflow, where C_{OM} corresponds to annual operation and maintenance costs and r_{e} and r_{i} correspond to escalation and inflation rates, respectively.

Implementation

In order to automatically search for possible locations for recovering dissipated energy (from zones with excessive pressures) and select and design the most adequate turbine, an integrated numerical tool implementing the proposed methodology was developed using the C++ programming language. The hydraulic simulator *EPANET 2.0* was integrated into the developed tool in order to perform the main hydraulic simulation. The incorporation of *EPANET* in the developed application was performed using the *EPANET* programming toolkit. The implemented methodology essentially consists of three main steps: (1) find locations with significant available hydraulic power, (2) select adequate types of turbines for such locations, and (3) perform a preliminary feasibility analysis.

The implemented procedures to perform step A are described in the algorithms presented in Figs. S1 and S2. In procedure *sitesLocation1()*, a hydraulic simulation of the network under analysis is performed. The obtained values of flow rate and head drop in each link for all time periods of the simulation are used to compute the variation and total available hydraulic power in each potential site.

The procedure listed in Fig. S2 consists of the analysis of each selected potential site by installing a virtual PRV at the end of each pipe. The minor head loss coefficient initially attributed to the PRV is $K_{\text{m}} = 0$. For each scenario (1 scenario per selected site or pipe), a search for the optimal value of K_{m} is performed by calling the *optimalValveCoeff()* function. This function, described in Fig. S3, (1) replaces, in each iteration, the loss coefficient K_{m} by a new value; (2) performs a hydraulic simulation of the network to compute the energy dissipated by the valve; and (3) obtains the new values of pressure at the demand nodes. If the nodal pressures do not violate the imposed constraint [as formulated in Eq. (5)] and the computed value of dissipated energy is maintained or increased, then the changes performed in the network model are saved and a new value of K_{m} is tested. Otherwise, the value of K_{m} and the corresponding dissipated energy (the potentially recovered energy) are returned. In this work, the new value of K_{m} is searched through a constant λ steepest descent optimization procedure. However, other more efficient procedures can be used.

The second main step executed in the developed tool consists of the selection of the types of turbines that are adequate for each different scenario, according to the head ranges presented in Table 1. This step consists of two procedures: (1) assess the technical feasibility; and (2) evaluate the financial feasibility of the selected turbines, according to Table 1. The procedure to assess the financial feasibility provides, for each scenario, (1) the predicted annual income for each type of turbine associated with each scenario; (2) the total investment, including the cost of the turbine and installation, generator, engineering, and civil works; and, finally, (3) the payback time for each type of turbine.

Results

Case Study Description

The Italian network analyzed in this work, the Napoli Est water distribution system, was introduced by Fontana et al. (2012), who gently provided the corresponding *EPANET* model. Fontana et al. (2012) tested the use of PRVs and PATs for loss reduction and energy recovery. The Napoli Est network serves approximately 8% of the Naples municipality, which corresponds to 65,000–70,000 inhabitants. The elevation ranges between 11 and 78 m above sea level (Fontana et al. 2012). This gravity-fed distribution network, represented in Fig. 2(a), is composed of 349 pipes with diameters ranging from 40 to 1,000 mm and 251 nodes, of which 151 are demand nodes [values of pressure in such nodes at 8 a.m. are provided in Fig. 2(b)]. The network is supplied by the San Sebastiano

	Turbine type	Efficiency equations
Reaction	Francis (10 < H < 350)	$\eta_{\text{F, peak}} = \left[0.919 - \left(\frac{N_Q-56}{256}\right)^2 + \left(0.81 + \left(\frac{N_Q-56}{256}\right)^2\right)\left(1 - \frac{0.789}{D_t^{0.2}}\right)\right] - 0.0305 + 0.005R_m$
		$\eta_{\text{F,below}} = \left[1 - \left(1.25\left(\frac{Q_{peak}-Q_t}{Q_{peak}}\right)^{3.94-0.0195N_Q}\right)\right]\eta_{\text{F, peak}}$ (flow below peak)
		$\eta_{\text{F,above}} = \eta_{\text{F, peak}} - \left[\left(\frac{Q_t-Q_{peak}}{Q_d-Q_{peak}}\right)^2\left(\eta_{\text{F, peak}} - (1-0.0072N_Q^{0.4})\eta_{\text{F, peak}}\right)\right]$ (flow above peak)
	Kaplan (2 < H < 40)	$\eta_{\text{K,peak}} = 0.905 - \left(\frac{N_Q-170}{700}\right)^2 + \left(0.095 + \left(\frac{N_Q-170}{700}\right)^2\right)\left(1 - \frac{0.789}{D_t^{0.2}}\right) - 0.0305 + 0.005R_m$
		$\eta_K = \left[1 - 3.5\left(\frac{0.75Q_d-Q_t}{0.75Q_d}\right)^6\right]\eta_{\text{K,peak}}$
	Propeller (2 < H < 40)	$\eta_{prop} = \left[1 - 1.25\left(\frac{Q_d-Q_t}{Q_d}\right)^{1.13}\right]\eta_{\text{K,peak}}$
		$R_m = 4.5$ (turbine manufacture/design coefficient), $D_t = k_1 Q_d^{0.473}$ (runner diameter) and $N_Q = k_2 H_t^{-0.5}$ (specific speed based on flow), where $k_1 = 0.46$, $k_2 = 600$ for Francis turbines or 800 for Kaplan/propeller turbines.
Impulse	Pelton (50 < H < 1300)	$\eta_P = \left[1 - (1.31 + 0.025n_{jet})\left\lvert\frac{Q_d-Q_t}{Q_d}\right\rvert^{(5.6+0.4n_{jet})}\right]0.864\left(\frac{49.4H_t^{0.5}n_{jet}^{0.02}}{31\left[H_t(Q_d/n_{jet})\right]^{0.5}}\right)^{0.04}$, $1 \le n_{jet} \le 6$
	Turgo (50 < H < 250)	$\eta_T = 0.3\eta_P$
	Cross-flow (3 < H < 250)	$\eta_{CF} = 0.79 - 0.15\left(\frac{Q_d-Q_t}{Q_d}\right) - 1.37\left(\frac{Q_d-Q_t}{Q_d}\right)^{14}$
	Type of cost	**Cost equations (CAD $)**
Turbine and governor	Francis	$C_{t,F} = 0.17n_{turb}^{0.96}J_tK_tD_a^{1.47}\left[(13+0.01H_d)^{0.3}+3\right]10^6$
	Kaplan	$C_{t,K} = 0.27n_{turb}^{0.96}J_tK_tD_a^{1.47}\left(1.17H_d^{0.12}+2\right)10^6$
	Propeller	$C_{t,prop} = 0.125n_{turb}^{0.96}J_tK_tD_a^{1.47}\left(1.17H_d^{0.12}+4\right)10^6$
	Pelton/Turgo	$C_{t,P/T} = \begin{cases} 3.47n_{turb}^{0.96}\left(P_u/H_d^{0.5}\right)^{0.44}10^6, & \text{if } P_u/H_d^{0.5} > 0.4 \\ 5.34n_{turb}^{0.96}\left(P_u/H_d^{0.5}\right)^{0.91}10^6, & \text{if } P_u/H_d^{0.5} \le 0.4 \end{cases}$
	Cross-flow	$C_{t,CF} = 0.5C_{t,P/T}$
		$D_a = 0.482Q_d^{0.45}$ (approximated turbine runner diameter, in m), $n_{turb} = 1$ (number of turbines), $J_t = 1.1$ if $H_d > 25$ m, otherwise $J_t = 1$ (higher cost vertical axis turbine factor to account for cost increase with vertical axis at heads above 25 m), $K_t = 0.9$ if $D_a < 1.8$ m, otherwise $K_t = 1$ (lower cost small horizontal axis turbine factor to account for cost decrease with small horizontal axis units) and $P_u = 7.53Q_dH_d/1000$ (unit capacity, in MW)
Engineering		$C_{eng} = 0.04 \times 10^6\left(P_u/H_d^{0.3}\right)^{0.54}$
Generator and control		$C_{gen} = 0.82 \times 10^6 n^{0.96}\mathrm{G}F_g\left(P_u/H_d^{0.28}\right)^{0.9}$, G = 0.9 if $P_u < 1.5$ (if using induction generators); $F_g = 0.75$ if $P_u < 10$ or 1 if $P_u \ge 10$ (lower cost generator factor)
Installation		$C_{inst} = 0.15\left(C_t + C_{gen}\right)$
Civil works		$C_{civ} = 10^6\frac{1.97}{n_{turb}^{0.04}}f_{civil}\left(P_u/H_d^{0.3}\right)^{0.82}$, $f_{civil} = 0.44$ for an existing dam or 1.0 if no dam exists (civil cost factor)

Fig. 1. Equations used to compute the turbine efficiencies and costs (data from European Small Hydropower Association 2004b)

reservoir, whose pattern of water level variation for the period of simulation considered in this work (72 h) is represented in Fig. 2(c). Using *EPANET 2.0* for the simulation of the network, the maximum pressure obtained is observed in the junction node J187 at 6 a.m. of each simulated day. The minimum pressures are observed in the junction nodes J182 and J183. As can be observed in Fig. 2(d), the average value of pressure in the entire network is greater than 70 m, meaning that, considering the 25 m of minimum pressure required, the network presents an excess of pressure. Although Fontana et al. (2012) have defined 25 m as the minimum pressure for the demand nodes, in their work, pressures above 20 m were considered acceptable.

Locating and Assessing Potential Sites for Energy Recovery

Following the proposed methodology, at the initial stage, the hydraulic energy available in each pipe of the network was computed.

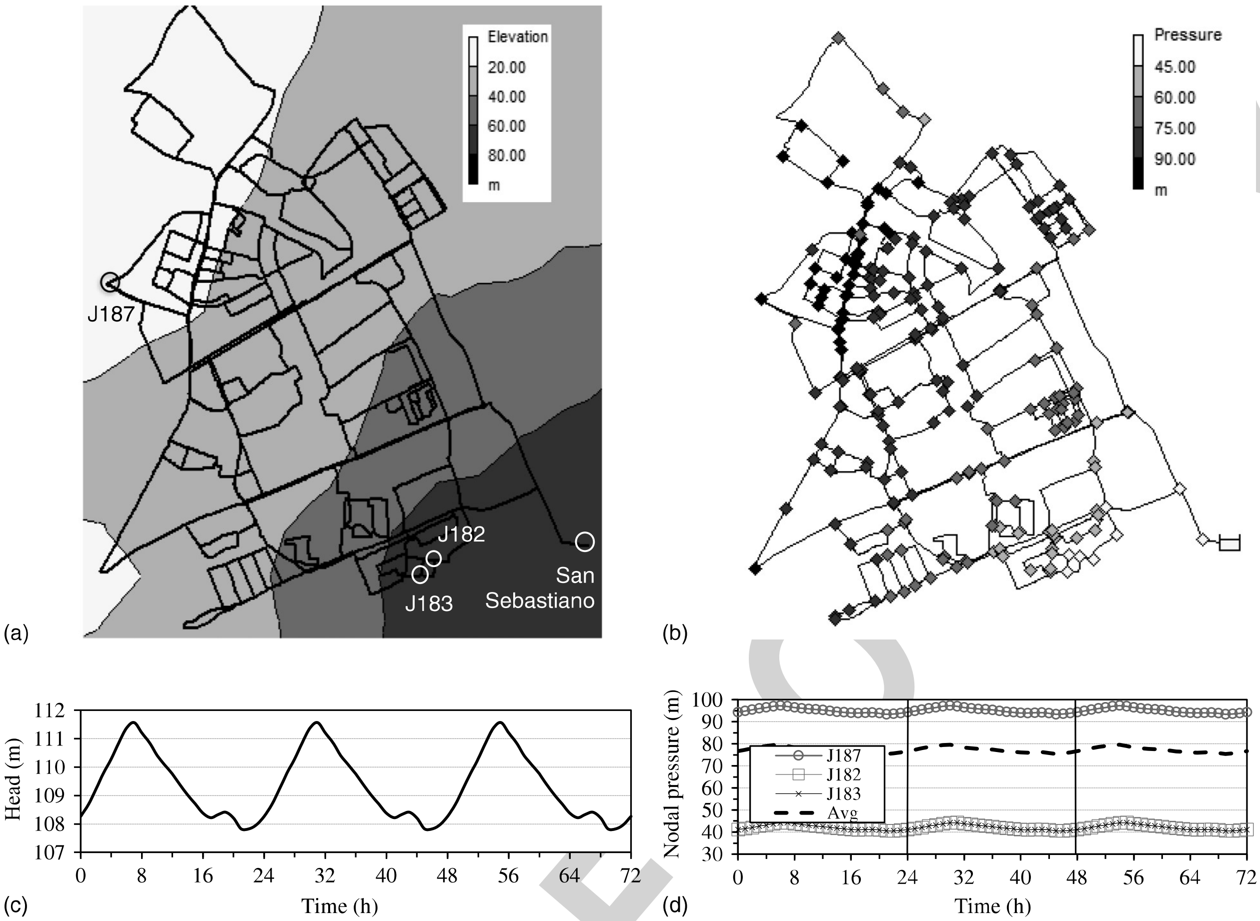


Fig. 2. Results of the Napoli Est network simulation, including (a) values of elevation; (b) nodal pressures at 8 a.m.; (c) the pattern defined for the water level variation in the San Sebastiano reservoir; and (d) pressure variation in the nodes with the maximum and minimum values identified, as well as the average pressure variation in all demand nodes of the network

The best scenarios obtained, S1 to S8, are depicted in Table 1 and identified in Fig. 3. The presented flow ranges correspond to the values obtained from the flow-duration curve analyzed for each pipe and considering the values between the minimum and mean flow rates. The available hydraulic energy in each pipe was computed for all hourly time-steps of the 3-day simulation. The obtained results are also compared with the ones analyzed by Fontana et al. (2012), represented by scenarios A, B, and D.

As can be observed, from the eight best obtained results, three of the pipes correspond to the same pipes identified by Fontana et al. (2012) as locations with higher potential for water loss reduction and energy production. However, when taking into account only energy production, other pipes reveal substantially higher potential, such as the scenarios S1 and S2.

In the stage of implementing virtual PRVs, the selection of the most profitable head loss coefficient for each valve was performed considering a minimum pressure limit of 25 m in the demand nodes. Table 2 shows the results for the selected scenarios obtained for each installed valve. A fixed step size of $d^j = 500$ was used.

As can be observed, the implemented methodology [that obtains an adequate head loss coefficient for the valves by maximizing energy production while maintaining the minimum required pressures in the network—Eq. (5)] provided different results from the ones presented by Fontana et al. (2012). In fact, for the common sites (i.e., in pipes P354, P358, and 1), the potential recoverable energy is higher than that predicted by Fontana et al. (2012). However, it should not be forgotten that their main objective was water loss reduction and not energy production, unlike the current work.

The results demonstrated that the pipes presenting higher combinations of flow rate and head drop do not necessarily present the highest potential for energy recovery. This is explained by the effects of valve or turbine installation on the network's pressure drop, demonstrating the importance of performing the simulation of the network accounting with such devices.

The sites that presented the largest values of potentially recoverable power were pipes 1, P354, and P29. Although the valves located in pipes 1 and P354 present large values of flow rate, the valve in pipe P29 presents high potential essentially because of the head drop. The hourly FDCs for these three sites are presented in Fig. 4 and illustrate the usable flow range for energy generation. For the three cases, it can be observed that the mean flow (the value to be used as the design flow) is equaled or exceeded more than 60% of the time.

Selecting the Most Adequate Turbines and Testing Possible Choices

According to the operation range of each turbine type, the results obtained for the eight selected scenarios are presented in Table 2. As can be observed, scenario S6 (located in pipe P358) presents a very limited and low head range where the turbines typically do not operate. For this reason, only a specific type of pump-as-turbine

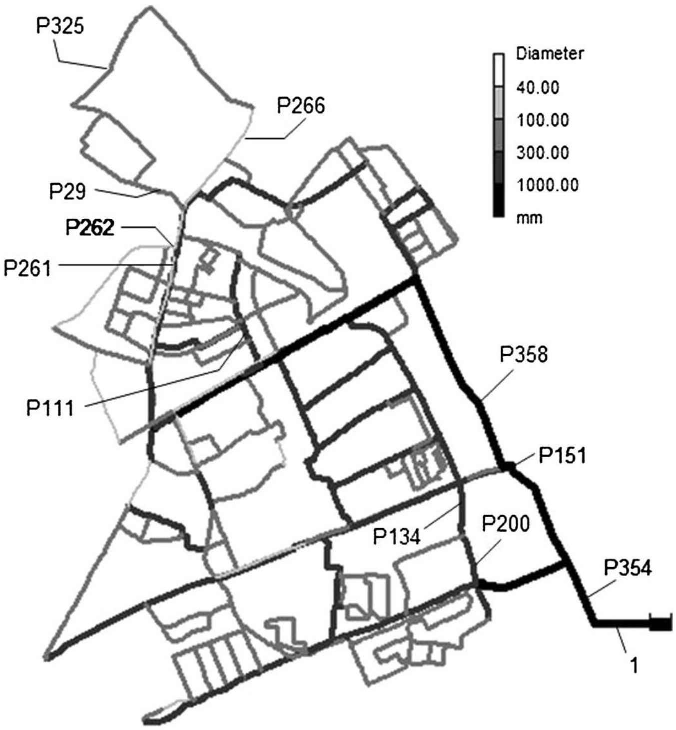


Fig. 3. Location and diameters of the sites that represent the largest potential for energy recovery and also of the sites discussed in the work of Fontana et al. (2012)

could eventually be used in such a site. In fact, Choulot et al. (2012) mentioned that PATS are the most adequate for values of installed power inferior to 30 kW, which means that, according to the available hydraulic power, a PAT would be the most adequate type of turbine for scenarios S2 (9.47 kW), S5 (2.89 kW), S6 (16.90 kW), and S7 (3.21 kW).

The results concerning the adequate specific speed N_Q (metric units), the approximated runner diameter D_a, and efficiency for each type of turbine η_{turb}, according to the design flow and head Q_d and H_d, are provided in Table 3. The daily potential net recoverable energy E_{net}, considering the obtained values of efficiency for each distinct type of turbine, is also presented.

Comparing the results in terms of turbine efficiency and hence the potential net recoverable energy, the Kaplan/propeller-type turbines were demonstrated to be slightly more profitable in all the scenarios because of their higher efficiency values. However, when selecting a turbine, the range of flow operation should also be taken into account because distinct turbine types present distinct variations in efficiency when operating at flow rates inferior to the design flow. An adjustable Kaplan, for instance, demonstrates more satisfactory operation (higher efficiencies) over a wide range of flow variations when compared with a propeller with fixed guide vanes and blades (European Small Hydropower Association 2004b; Choulot et al. 2012). This means that an adjustable Kaplan turbine would be more adequate for energy recovery in water supply and distribution networks.

Because the values of potential recoverable energy are obtained from the network simulation using a standard PRV, it is important to understand the differences when modeling a turbine using real curves. For this reason, an analysis was performed on the three best obtained scenarios, S3, S4, and S8, using data of turbines existent in the market. An example of a real curve from Mavel's Kaplan-type turbines [Fig. 5(a)] was used. The turbine selected was the Mavel TM3_18″ (Mavel 2015). The curves presented by Fontana et al. (2012) for the two reverse pumps NC100-200 and NC150-200 [Figs. 5(b and c)] were also used for comparison purposes.

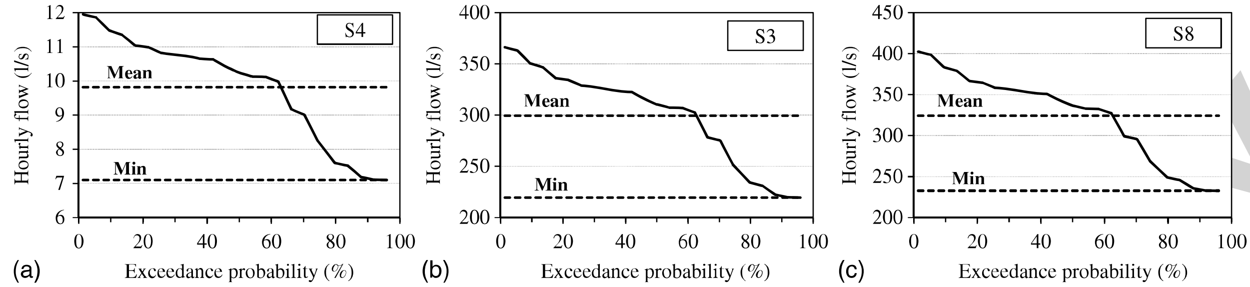
The turbine operations were simulated in *EPANET* by replacing, in each scenario, the existent PRVs with a general purpose valve (GPV). The GPV head loss curve was obtained in accordance with the turbine hydraulic curve, which provides the recovered head for a certain flow rate.

Different turbines were selected for each scenario according to the flow and head characteristics of the sites. Table 4 presents the turbines tested in each selected scenario and the corresponding results in terms of energy recovered, as well as the replicated results of Fontana et al. (2012) for a comparative analysis. All the

Table 2. Results of Dissipated Energy in the Pressure Reduction Valves (PRVs) Individually Installed in Each Selected Scenario and Types of Turbines That Can Be Installed According to the Head Ranges

Scenarios	Pipe ID	PRV K_m (-)	Flow range, minimum-mean (l/s)	Head loss, min-mean (m)	E_{recov} (kWh/day)	Type of turbine
S1	P325	1,500	4.0–6.1	20.09–47.95	74.56	F, CF, K/P, PAT
S2	P262	1,000	0.6–1.0	10.16–35.26	9.47	F, CF, K/P, PAT
S3	P354	3,000	219.6–299.4	11.94–22.73	1,694.28	F, CF, K/P, PAT
S4	P29	3,000	7.1–9.8	24.69–48.31	118.26	F, CF, K/P, PAT
S5	P266	1,000	0.4–0.7	6.36–16.20	2.89	CF, K/P, PAT
S6	P358	1,000	53.7–73.7	0.48–0.92	16.90	PAT
S7	P261	500	0.5–0.9	3.76–13.56	3.21	CF, K/P, PAT
S8	1	3,000	219.8–299.5	11.97–22.75	1,696.50	F, CF, K/P, PAT
A	1	1,000	232.8–324.2	0.30–0.41	723.35	—
B	P151	94,000	89.2–123.5	6.41–12.62	389.47	—
	P200	4,000	29.9–41.4	6.95–13.63	140.91	—
			Scenario total recoverable energy:			
	530.38	—	—	—	—	—
D	P111	222,000	3.2–4.0	1.43–2.30	2.26	—
	P134	114,000	10.2–13.7	7.62–13.96	47.48	—
	P354	1,000	222.2–305.3	4.08–7.89	600.94	—
	P358	73,000	35.7–47.8	7.69–14.08	167.07	—
			Scenario total recoverable energy:			
	817.76	—	—	—	—	—

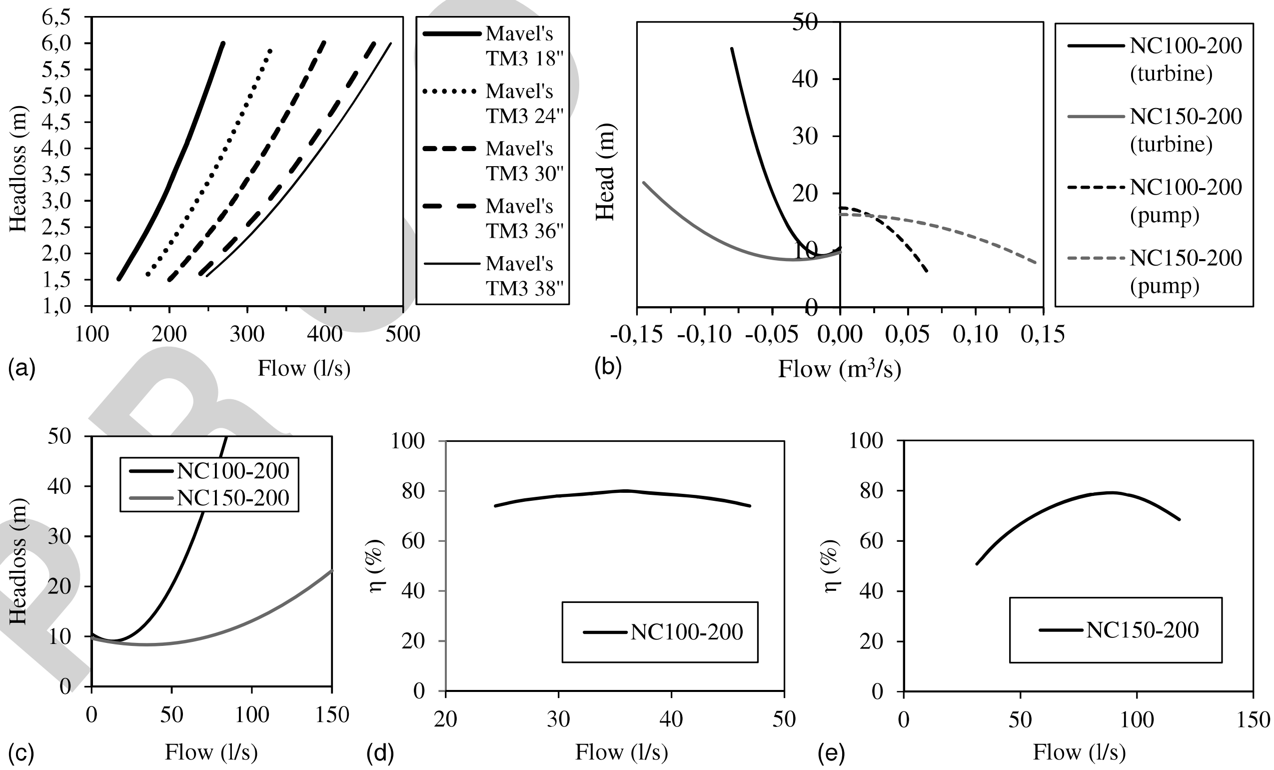
Note: CF = Cross-flow; F = Francis; K = Kaplan; P = Propeller; PAT = Pump-as-turbine. The energy results proposed by Fontana et al. (2012) are also presented.



F4:1 F4:2 **Fig. 4.** Flow-duration curves (FDCs) for the three sites that presented the largest potential for energy recovery without compromising the pressure requirements: (a) S4; (b) S3; and (c) S8

12 **Table 3.** Characteristics Obtained for Each Type of Turbine According to the Design Flow and Head Specified for Each Scenario (Excluding the Scenarios Adequate for PATs) and the Resulting Daily Net Energy That Can Be Recovered

	Scenarios	Location (pipe ID)	Q_d (m^3/s)	H_d (m)	E_{gross} (kWh/day)	Turbine type	N_Q (-)	d (m)	η_{turb} (-)	E_{net} (kWh/day)	
T3:1											
T3:2	S1	P325	0.006	47.95	74.56	Francis	86.6	0.041	0.813	60.62	
						Kaplan/propeller	115.5	0.041	0.841	62.70	T3:3
						Cross-flow	—	—	0.790	58.90	T3:4
T3:5	S3	P354	0.300	22.73	1,694.28	Francis	125.8	0.260	0.790	1,338.57	
						Kaplan/propeller	167.8	0.260	0.894	1,514.48	T3:6
						Cross-flow	—	—	0.790	1,338.48	T3:7
T3:8	S4	P29	0.009	48.31	118.26	Francis	86.3	0.050	0.819	96.81	
						Kaplan/propeller	115.1	0.050	0.846	100.10	T3:9
						Cross-flow	—	—	0.790	93.43	T3:10
T3:11	S8	1	0.300	22.75	1,696.50	Francis	125.8	0.260	0.790	1,340.54	
						Kaplan/propeller	167.7	0.260	0.894	1,516.47	T3:12
						Cross-flow	—	—	0.790	1,340.24	T3:13



F5:1 F5:2 F5:3 **Fig. 5.** Real curves for the simulation of different types of turbines, including (a) Mavel's Kaplan-type micro turbine head loss curves; (b) hydraulic curves of the two reverse pumps used by Fontana et al. (2012); (c) the corresponding head loss curves used for the PAT simulation in *EPANET*, as well as the corresponding efficiency curves (Caprari 2006) for the PATs; (d) NC 100-200; and (e) NC150-200

13 **Table 4.** Results Obtained from the Simulation of the Network Operation Considering the Installation of Different Turbines Available in the Market

Scenarios	Location (pipe ID)	Simulated turbines	E_{gross} (kWh/day)	η_{turb} (%)	E_{net} (kWh/day)	$\sum E_{net}$ (kWh/day)
S3	P354	Mavel TM3_18″	679.05	89.40	607.07	—
		3 parallel NC150-200	1,098.26	72.04	770.86	—
S4	P29	NC100-200	27.76	38.50	11.10	—
S8	1	Mavel TM3_18″	680.50	89.40	608.37	—
A	1	3 parallel NC150-200	991.12	72.01	771.68	771.68
B	P151	NC150-200	428.54	67.31	273.36	378.92
	P200	NC100-200	148.61	71.69	105.56	—
D	P111	—	—	—	—	725.37
	P134	—	—	—	—	—
	P354	3 parallel NC150-200	952.73	74.75	703.65	—
	P358	NC100-200	49.22	42.30	21.72	—

Note: Results obtained from the reproduction of Fontana et al. (2012) scenarios are also presented.

scenarios presented nodal pressures that were always greater than 25 m.

The rotational speed is 1,550 rpm for the NC100-200 and NC150-200 PATs. The power output is 5 to 20 kW for the Mavel's TM3 micro turbines (Mavel 2015). For the turbine efficiencies, the curves presented in Figs. 5(d and e) were used for the NC100-200 and NC150-200, respectively. Because the Mavel's efficiency curves could not be obtained from the manufacturer, the efficiency was computed using the formulae proposed for Kaplan-type turbines.

For scenario S3, the use of only one Kaplan-type turbine (Mavel TM3_1800″) allowed recovery of almost the same amount of daily energy when compared with the use of three parallel PATs (NC150-200), while maintaining the required pressures in the network. It can also be observed that, for the same location (pipe P354), different scenarios produced different results. In the scenario proposed by Fontana et al. (2012) (scenario D), the same three parallel turbines installed in the same location were not capable of recovering the same amount of energy because of the distinct operational conditions of the network: an additional PAT operating in another location of the network (pipe P358) and also two PRVs (at pipes P111 and P134).

Results demonstrate that, even performing a preliminary analysis on the potential recovered energy of the networks, the real energy recovered will be highly dependent on the turbine selection from the range available on the market. Only a final simulation of the network operation with the information of a specific turbine can provide more precise results. However, the applied methodology demonstrates quite good results for a preliminary analysis and can be used as a support for turbine selection.

Preliminary Financial Analysis

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Financial results obtained from the developed tool for the distinct types of turbines are presented in Table 5. Despite PAT cost computation not being included in the developed tool, the price ranges provided by Fecarotta et al. (2015) are used as a reference. For the installation costs, 15% of the PAT cost was also considered. The presented financial analysis corresponds to a preliminary (and therefore simplified) analysis. An accurate payback period estimation should address maintenance and operation costs (including water costs and business activities), turbine lifespan, and the savings from leakage reduction. In this preliminary analysis, only annual operation and maintenance costs C_{OM} are taken into account

14 **Table 5.** Results of the Preliminary Cost Analysis for the Selected Scenarios

Scenarios	Turbine type	E_{recov} (kWh/day)	E_{recov} (MWh/year)	C_{EP} (€/year)	C_{inv} (€)	C_{OM} (€/year)	SP (years)
S1	Francis	60.62	22.13	48,68	108,16	487	2.5
	Kaplan	62.70	22.88	5,034	12,300	503	2.7
	Propeller	62.70	22.88	5,034	9,455	503	2.1
	Cross-flow	58.90	21.50	4,730	5,491	473	1.3
S3	Francis	1,338.57	488.58	107,487	139,335	10,749	1.4
	Kaplan	1,514.48	552.79	121,613	152,730	12,161	1.4
	Propeller	1,514.48	552.79	121,613	120,896	12,161	1.1
	Cross-flow	1,338.48	488.54	107,480	110,922	10,748	1.1
	3 PATs[a]	1,220.56	445.50	98,011	127,888–141,659	9,801	1.4–1.6
S4	Francis	96.81	35.34	7,774	14,346	777	2.1
	Kaplan	100.10	36.54	8,038	16,292	804	2.3
	Propeller	100.10	36.54	8,038	12,568	804	1.7
	Cross-flow	93.43	34.10	7,502	7,779	750	1.2
	1 PAT[b]	45.53	16.62	3,656	4,618–9,208	366	1.4–2.8
S8	Francis	1,340.54	489.30	107,645	139,357	10,764	1.4
	Kaplan	1,516.47	553.51	121,772	152,756	12,177	1.4
	Propeller	1,516.47	553.51	121,772	120,920	12,177	1.1
	Cross-flow	1,340.24	489.19	107,621	110,971	10,762	1.1

[a]Using as reference the 3 parallel PATs NC150-200 and the corresponding efficiency curves.
[b]Using as reference the PAT NC100-200 and the corresponding efficiency curve.

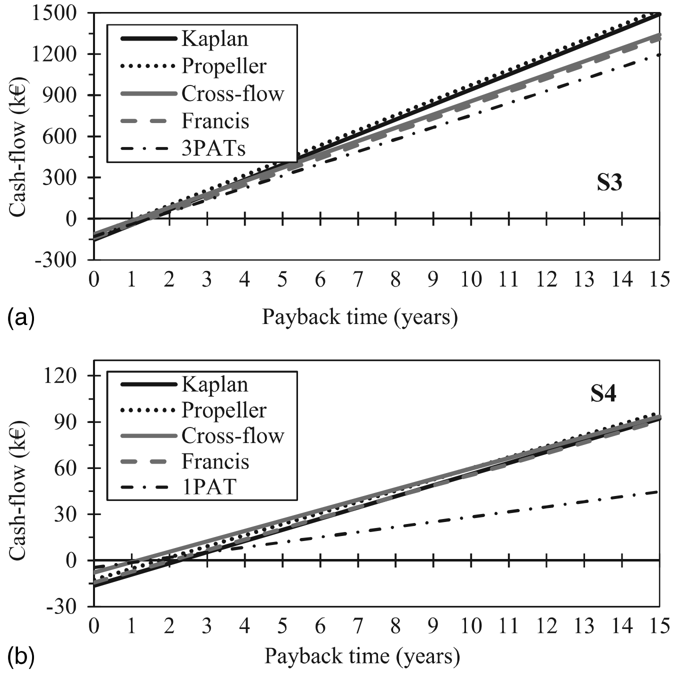

Fig. 6. Cash-flow analysis for the selected scenarios over a period of 15 years: (a) S3; and (b) S4

to compute the payback. As recommended by the Colorado Energy Office (2015), the estimation of such costs was based on 10% of the project's total annual income. Because the inflation and escalation rates (r_i and r_e) were not considered in the analysis, the annual income corresponds to the income from the annual energy production.

The energy tariff considered to compute the annual income C_{EP} was the Italian tariff, defined as 0.220 €/kWh (Fontana et al. 2012). In order to present all the results in Euros, the Canadian dollar was considered to have a value of 0.6953 €, and the costs were converted accordingly.

As shown in Table 5, in the two scenarios where the PATs are also compared, the cross-flow turbines present investment costs lower or within the cost range considered for PATs. In comparing the cross-flow turbines with the other types, although presenting lower efficiencies, the cross-flow turbines present the lowest initial investment costs and also the fastest return on investment (payback periods of approximately 1.1 to 1.3 years). For the scenarios with the highest annual energy production, S3 and S8, the payback time does not differ significantly between the different types of turbines.

A cash-flow analysis during the first 15 years for scenarios S3 and S4 is presented in Fig. 6. For scenario S3, the three parallel PATs are capable of reaching long-term profits in comparison with the profits of the other turbines. However, for scenario S4, the profits from the selected PAT are significantly lower than the ones of the other turbines (a difference of approximately 50 k€ after 15 years).

As already mentioned by Fecarotta et al. (2015), it should be remembered that the results obtained from this analysis depend on the considered tariff. For other countries under distinct conditions of electricity selling price and possible incentives, the results can be different.

Conclusion

The evaluation and design of a hydro power scheme for energy recovery in a water supply system is not straightforward because it requires time-consuming and complex analyses. This fact can be pointed out as the main reason water utilities do not invest in this type of solution. For this reason, a tool that automatically determines all the possibilities for the implementation of this type of solution while providing preliminary feasibility analyses could boost the adoption of this type of efficiency measures.

A numerical tool that makes use of the hydraulic model of the network to search by (and assess) locations for the installation of distinct types of turbines with the main objective of maximizing energy recovery is presented in this work. At the same time, technical and financial feasibility analyses are provided, which includes the selection and preliminary design of appropriate turbines and the corresponding payback time of the project. The search for site locations is performed in all links of the network, including the options of (1) installing a turbine at the end of a certain pipe or (2) replacing a valve with a turbine.

The implemented methodology was demonstrated to be effective through the comparison of results. Moreover, it was possible to conclude that, considering the maximization of energy production as single objective, other sites in the network with higher potential can be identified.

From the obtained results, it can be concluded that the financial feasibility analysis is decisive in the choice of a certain type of turbine for each particular location. The lowest-cost turbine does not necessarily represent the fastest return on investment or the highest revenues in a long-term period. In fact, such parameters are largely dependent on the site characteristics.

Notation

The following symbols are used in this paper:

C_{EP} = annual income from energy production;
C_{OM} = operation and maintenance costs;
C_{civ} = cost of civil works;
C_{dev} = development costs;
C_{energy} = sale price of energy;
C_{eng} = engineering costs;
C_{equip} = energy equipment and installation costs;
C_{gen} = generator and control costs;
C_{in} = annual cash inflow (income);
C_{inst} = energy equipment installation cost;
C_{inv} = investment cost (total initial costs of project);
C_{out} = annual cash outflow (expenses);
$C_{t,CF}$ = cost of cross-flow turbine;
$C_{t,F}$ = cost of Francis turbine;
$C_{t,K}$ = cost of Kaplan turbine;
$C_{t,P/T}$ = cost of Pelton/Turgo turbines;
$C_{t,prop}$ = cost of propeller turbine;
D = pipe diameter;
d = search direction;
D_a = approximated turbine runner diameter;
D_{out} = turbine outside runner diameter;
D_t = turbine runner diameter;
E_{recov} = potential recoverable energy;
f_{civil} = civil cost factor;
g = gravitational acceleration;
H = head;
H_d = turbine design head;
H_{gross} = gross head;
H_{net} = net head;
H_t = turbine rated head;

h_m = minor head losses;
J_t = higher-cost vertical axis turbine factor;
K_m = minor loss coefficient;
K_t = lower-cost vertical axis turbine factor;
k_1, k_2 = constants;
N_Q = dimensionless turbine specific speed based on flow;
n_{jet} = number of jets;
n_{turb} = number of turbines;
P = pressure;
P_d = power to be installed in hydro power scheme;
P_{gross} = gross power;
P_{net} = net power;
P_u = approximated capacity of unit hydro power scheme;
Q_d = turbine design flow;
Q_{peak} = turbine peak efficiency flow;
Q_t = turbine rated flow;
R_m = turbine manufacture/design coefficient;
r_e and r_i = escalation and inflation rates;
v = fluid velocity;
Z = elevation;
γ = fluid-specific weight;
η_{CF} = cross-flow turbine efficiency;
$\eta_{F,above}$ = Francis turbine efficiency for flows above Q_{peak};
$\eta_{F,below}$ = Francis turbine efficiency for flows below Q_{peak};
$\eta_{F,peak}$ = Francis turbine peak efficiency;
η_K = Kaplan turbine efficiency;
$\eta_{K,peak}$ = Kaplan turbine peak efficiency;
η_P = Pelton turbine efficiency;
η_T = Turgo turbine efficiency;
η_{gear} = gearbox efficiency;
η_{gen} = generator efficiency;
η_{prop} = propeller turbine efficiency;
$\eta_{prop,peak}$ = propeller turbine peak efficiency;
η_t = efficiency of set turbine, transformer, generator, and gearbox;
η_{transf} = transformer efficiency;
η_{turb} = turbine efficiency;
λ = search step size; and
ρ = fluid density.

Supplemental Data

Figs. S1–S3 are available online in the ASCE Library (www.ascelibrary.org).

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