Pump as turbine implementation in a dynamic numerical model: cost analysis for energy recovery in water distribution network

Mauro De Marchis and Gabriele Freni

ABSTRACT

In complex systems characterized by the presence of private tanks and water scarcity conditions, water managers usually apply intermittent distribution, trying to reduce the water volumes supplied to the users and pipe leakages, or use pressure reduction valves for controlling pressure in the network. The application of pumps as turbines (PATs) appears as an alternative and sustainable solution to either control network pressure or produce energy. In the present paper, the economic benefit of PAT application in water distribution networks was investigated in a small district of Palermo network (Italy). The analysis of energy recovery, carried out by means of a numerical model based on the method of characteristics, shows that PATs can lead to a very attractive economical benefit in terms of energy production.

Key words | dynamic network model, energy recovery, pump as turbine, renewable energy, water distribution network

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INTRODUCTION

Energy plays an important role in almost all areas of human and commercial activities. In water distribution networks (WDNs), the operational costs are growing especially in developed and emerging countries, where an increase of the water demand occurs. The energy used to pump and treat water for urban uses represents 2–3% of the world's energy consumption (Barry 2007), which could be reduced by at least 25% through cost-effective actions. The strong connection between water and energy in WDN gives rise to programs, such as Watergy (see Barry 2007), whose aim is to realize significant energy, water and monetary savings through technical and managerial changes. Several studies were carried out in order to investigate the possibility to recover energy in WDNs, considering mini- and micro-hydropower plants. Unfortunately, the high equipment costs prevent them from having a widespread application in water systems. Pumps are relatively cheap and simple devices, characterized by low maintenance cost and are readily available in most of the world, and several studies showed that the use of pumps as turbines (PATs) can be considered a good alternative for power generation. Despite this, some issues are still open and need further analysis. Recently, Laghari *et al.* (2013) showed that among renewable energy sources, large hydropower, biomass, solar heating system, wind and mini-hydro and waste-to-energy plants are able to cover a significant amount of electricity demand. Unfortunately, mini-hydro energy represents a minor contribution to renewable energy production despite its technology being established, reliable and efficient. Furthermore, Laghari *et al.* (2013) showed that almost 60% of the installed mini-hydro capacity in the world is achieved by China, while the USA covers 8%, the whole European Union less than 12% and Italy covers only a quota of 3%. Despite this, increased interest in renewable energy sources puts the focus of further investigation on small hydropower development. It is estimated that the world potential of small hydropower is around 180,000 MW (Singh & Upadhyay 2014).

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PATs, characterized by lower equipment costs, can be an attractive alternative to the classical turbine, especially for small size power plants (<40–50 kW). An interesting analysis of the state-of-the-art of the pump running in turbine mode was recently carried out by Jain & Patel (2014), where the worldwide implementation of PATs and different manufacturing processes are described along with the limitations in implementation and the recommendations to improve their performance. The historical development of PATs is described focusing on experimental analysis, computational fluid dynamics (CFD) and economical benefits.

One of the most interesting experimental studies was conducted by Derakhshan & Nourbakhsh (2008b), where some relations were derived to predict the best efficiency point (BEP) on several low specific-speed centrifugal PATs. The simulations, where four PATs were tested, clearly showed that the centrifugal pump can operate as a turbine with different rotational speeds, various heads and flow rates. Singh & Nestmann (2010) carried out experimental analysis to investigate a wide range of PAT shapes. They accurately characterize these effects with respect to internal hydraulic variables over the complete operating region of the PAT. Furthermore, they tried to develop a theoretical model that involves the external operating variables on PAT and internal variables, using fundamental hydraulic and turbo machine laws. More recently, Nautiyal *et al.* (2011) carried out an experimental investigation of a centrifugal pump to study its characteristics in pump and turbine mode operation.

Some interesting analyses were focused to reproduce the behavior of reverse operation of centrifugal pumps through CFD. Unfortunately, until now CFD techniques have not been successful in predicting the correct performance of PATs. Derakhshan & Nourbakhsh (2008a), in fact, comparing theoretical, experimental and CFD results of a PAT, showed large deviations between CFD and experimental results. Later, Nautiyal & Kumar (2010) observed that despite the intense efforts carried out by several researchers, until now, the CFD is not yet an acceptable technique to predict PAT performance. This result has been later confirmed by Yang *et al.* (2012a) who compared PAT performance by means of theoretical, CFD and experimental methods. Nevertheless, Carravetta *et al.* (2012) stated that the CFD technique could be considered a valid alternative to experiments when there is a lack of the pump producers' characterization of PAT performance. CFD investigations were also carried out by Yang *et al.* (2012b). The authors, comparing the experimental result with the numerical one, found that numerical analysis over-predicts the experimental data. Indeed, the general trend of the efficiency, pressure head and shaft power curves were well captured.

Recently, PATs were investigated in terms of economic benefits. Arriaga (2010) presented the concept of PAT as a viable technical and economical alternative for the further pico-hydro development in the Lao People Democratic Republic located in South East Asia. Carravetta *et al.* (2012), through the comparison between experimental and CFD analysis, proposed a design method based on a variable operating strategy (VOS) to predict PAT behavior and to find the optimal solution which maximizes the produced energy in WDNs. Later, Carravetta *et al.* (2013a) extended the VOS methodology to investigate on best economic efficiency between a hydraulic regulation (HR) or an electrical regulation (ER), finding that HR is more flexible and efficient than ER. Recently, Puleo *et al.* (2013) analyzed the application of PATs in a real case through the development of a hydraulic model. They investigated the potential energy recovery from the use of centrifugal PATs in a WDN characterized by the presence of private tanks and intermittent service. The results showed that the energy production could be low and also discontinuous, questioning its efficacy, highlighting that further studies are required to investigate the possibility and the efficiency of the PATs to recover energy from the WDN. Fontana *et al.* (2012) presented a management strategy with two main folds: pressure control to reduce water losses and energy production. The authors applied, in a real WDN, a system of pressure reduction valves (PRVs) and PATs. Specifically, they tried to substitute the optimal location of PRVs with PATs, showing attractive profits and capital payback period (CPP). Despite the efficiency of PATs being lower than conventional hydro-turbines, a recent analysis carried out by Motwani *et al.* (2013) and based on the comparison between the annual life cycle cost (ALCC) of a PAT and of a Francis turbine, showed that the ALCC is much less for PAT than that of the Francis turbine, thus justifying further efforts in the study of PAT applications.

More recently, Carravetta *et al.* (2013b) showed that the installation of PATs in WDNs can provide interesting economic benefits for the manager of pipe networks in urban areas.

AIM OF THE STUDY

The current paper aimed to investigate energy recovery in WDN, replacing the classical energy dissipation devices, able to reduce pressure in the networks (i.e. PRVs), with PATs, that can be considered as a relatively cheap turbine and for which the technology can be considered established and efficient. Despite this, few studies are available, thus the present research is mainly focused to show the potential attractiveness of PAT installation (PI) in real distribution networks. The analysis was carried out in terms of energy and capital cost recovery. In the Mediterranean countries, users try to cope with water scarcity by means of private tanks; it was demonstrated (De Marchis *et al.* 2010, 2011) that these tanks deeply modify the WDN behavior. Moreover, the subsequent filling and emptying processes of the local tanks should modify pressure and discharges in the network pipes, causing modifications of energy production capability in WDNs. The energy recovery was analyzed by means of numerical simulations, carried out through a numerical model able to reproduce the effect of private tanks using a specific node demand model. The model takes care of the private tanks dimension, location and elevation. The water head and discharges are calculated through the method of characteristics (MOC). Specifically, the model already presented in Freni *et al.* (2014) was further developed including a specific dynamic module able to simulate PATs, recently investigated through experimental analysis by Derakhshan & Nourbakhsh (2008b). The model was applied to a district of Palermo network (Italy), characterized by intermittent distribution and by inequities in user water supply. A management strategy was performed, based on the economic analysis, and the payback period was calculated. The analysis of 24 hours energy production was carried out, taking into account the users satisfaction in term of water volume supplied in each node.

The research here proposed starts from the preliminary finding presented by De Marchis *et al.* (2013).

METHODOLOGY

In this section the numerical model and the case study are presented. The model description is divided into two parts: the discussion of the network hydrodynamic model, already presented in De Marchis *et al.* (2010), and the detailed description of the equations used for the PAT model are reported.

The network model

The numerical model is based on the resolution of the momentum and continuity equations, through the MOC.

Owing to the specific feature of the proposed model, occurring especially during the phase of filling of the pipes, some simplifying assumptions were needed. Based on the Liou & Hunt (1996) study, it is assumed that the air pressure at the water-front is always atmospheric and the wave-fronts are always perpendicular to the pipe axis and coincident with the cross-sections. For detailed discussion of the above hypothesis see De Marchis *et al.* (2010, 2011).

The 1D unsteady flow of the compressible liquid in the elastic pipe is described by the following system of equations:

$$(1+k)\frac{dV}{dt} + \alpha\frac{gdh}{cdt} + gJ_s + \frac{g}{c}\alpha V\sin(\theta) = 0 \tag{1}$$

$$(1+k)\frac{dV}{dt} - \beta\frac{gdh}{cdt} + gJ_s - \frac{g}{c}\beta V\sin(\theta) = 0 \tag{2}$$

where t is the time, $\boldsymbol{V}$ is the velocity averaged over the pipe cross-section, h is the water head, $\boldsymbol{g}$ is the acceleration due to gravity, c is the celerity of pressure waves, $\boldsymbol{\theta}$ is the slope of the pipeline and α and β are $(k+2–k\Phi_A)/2$ and $(k+2+k\Phi_A)/2$, respectively. Φ_A is a coefficient depending on the sign of the convective acceleration, according to the unsteady friction model of Vítkovský *et al.* (2006). Specifically, $\Phi_A = +1$ if $\boldsymbol{V}\frac{\partial \boldsymbol{V}}{\partial \boldsymbol{s}} \geq 0$, –1 if $V\frac{\partial \boldsymbol{V}}{\partial \boldsymbol{s}} < 0$. J_s is the head loss per unit length, function of the roughness. Wall roughness can deeply modify the mean velocity as recently demonstrated by De Marchis & Napoli (2012) and Milici *et al.* (2014), thus it must be accurately determined. The compatibility equations are valid along the proper positive and negative characteristic lines of equation that, introducing the unsteady friction model, read

$$C^{+}:\ \frac{ds}{dt} = +\frac{c}{\alpha} \tag{3}$$

$$C^{-}:\ \frac{ds}{dt} = -\frac{c}{\beta} \tag{4}$$

In the proposed numerical model the coefficient k was calculated at each time step toward the Vardy & Brown (2003) formulation, given by

$$k = \frac{\sqrt{c*}}{g} \tag{5}$$

with

$$c* = \begin{cases} 0.0476 & \mathrm{Re} < 2500 \\ 7.41 & \mathrm{Re} > 2500 \end{cases} \tag{6}$$

Equations (1) and (2) can be solved through the finite difference technique and read

$$h_j^{i,n+1} - h_{jm}^{i,n} + \frac{1+kc}{\alpha}\frac{c}{g}(V_j^{i,n+1} - V_{jm}^{i,n}) + \left[\frac{c}{\alpha}J_{jm}^{i,n} + V_{jm}^{i,n}\mathrm{sen}\theta^i\right]\Delta t_i = 0 \tag{7}$$

$$h_j^{i,n+1} - h_{jv}^{i,n} - \frac{1+kc}{\beta}\frac{c}{g}(V_j^{i,n+1} - V_{jv}^{i,n}) - \left[\frac{c}{\beta}J_{jv}^{i,n} - V_{jv}^{i,n}\mathrm{sen}\theta^i\right]\Delta t_i = 0 \tag{8}$$

where $V_j^{i,n+1}$ and $h_j^{i,n+1}$ are the velocity and the water head in the jth section (of abscissa $(j\text{–}1)L_i/N_i$) of the ith pipe at the time step $t^n + \Delta t$; θ^i is the slope of the ith pipe; j_m and j_v are the sections upstream and downstream to the jth section, respectively.

The time step advancement Δt_i^n, function of the length and of the celerity of the ith pipe, is calculated for each pipe and then the minimum value is chosen as the unique time step integration

$$\Delta t^n = \min_i \Delta t_i^n = \min_i \left(L_i^n/(N_i c_i)\right) \tag{9}$$

The compatibility equations for the pipelines connected to the node are resolved together with the continuity equation at each junction node, and the discharge provided to user tanks is calculated as a function of the water head. Specifically, the discharge $Q_{j,up}$ at the jth node entering the tank connected to the node can be obtained as

$$Q_{j,\mathrm{up}} = C_v \cdot a \cdot \sqrt{2g(h_j^i - h_{j,\mathrm{tank}})} \tag{10}$$

where C_v is the non-dimensional float valve emitter coefficient, a is the valve effective discharge area, g is the gravity acceleration, h_j^i is the water head at the jth node and $h_{j,\mathrm{tank}}^i$ is the height of the private tank.

Although previously more complex methods were considered to relate coefficients C_v and a to valve-opening rates, here constant values were used for both of the coefficients (Criminisi *et al.* 2009) which have been calibrated experimentally. Equation (10) can be used to calculate the discharge at nodes only when the floating valve is open, i.e. until the user tank is not entirely filled. Thus, this equation must be combined with the tank continuity equation, which can be written as

$$\begin{cases} Q_{j,\mathrm{up}} - D_j = \dfrac{dW_j}{dt} = A\dfrac{dH_j}{dt} & \text{for} \quad H_j < H_{j,\max} \\ Q_{j,\mathrm{up}} = 0 & \text{for} \quad H_j \geq H_{j,\max} \end{cases} \tag{11}$$

where D_j is the user water demand at the jth node, W_j is the volume of the storage tank connected to the node having area A, H_j is the tank water level and $H_{j,\max}$ is the maximum allowed water level in the tank (before the floating valve closes).

Further details on the numerical model can be found in Freni *et al.* (2014).

PAT model

The dynamic analysis of PATs is coupled with a numerical module able to reproduce PAT installation in the pipes of WDNs.

In the present analysis, several manufacturer catalogs were investigated to identify pumps satisfying the given turbine operating conditions (head and flow). The integrated model, given by the hydraulic and PAT sections, is structured in such a way that any kind of pump working in turbine mode can be simulated once the specific characteristic curve is given. In the present analysis in the PAT module the characteristic curves achieved by Derakhshan & Nourbakhsh (2008a) and Derakhshan & Nourbakhsh (2008b) through experimental analysis were used

$$\frac{H_t}{H_{tb}} = 1.0283 \cdot \left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.5468 \cdot \left(\frac{Q_t}{Q_{tb}}\right) + 0.5314 \tag{12}$$

$$\frac{P_t}{P_{tb}} = -0.3092 \cdot \left(\frac{Q_t}{Q_{tb}}\right)^3 + 2.1472 \cdot \left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.8865 \cdot \left(\frac{Q_t}{Q_{tb}}\right) + 0.0452 \tag{13}$$

where H (m), P (W), Q (m^3/s) are head, power, flow rate, respectively. Subscripts t and b are related to turbine and BEP.

Following, among others, Derakhshan & Nourbakhsh (2008a, b), PAT parameters are related to the specific rotational speed n (rps). Specifically, dimensionless head, discharge and power curves can be obtained through the equations

$$\Phi = \frac{g \cdot H}{n^2 \cdot D_{\mathrm{imp}}^2}; \quad \Psi = \frac{Q}{n \cdot D_{\mathrm{imp}}^3}; \quad \pi = \frac{P}{\rho \cdot n^3 \cdot D_{\mathrm{imp}}^5} \tag{14}$$

where D_{imp} is the impeller diameter.

The BEP is achieved maximizing the efficiency according to the equation

$$\eta_t = \frac{P_t}{\rho \cdot g \cdot Q_t \cdot H_t} \tag{15}$$

with ρ the water density.

As suggested by Derakhshan & Nourbakhsh (2008a), the prediction method is acceptable for centrifugal pumps with n (rpm) < 60.

In the present analysis 1D MOC method and 1D PAT curve is coupled to predict the energy recovery in WDN. Recently, Carravetta *et al.* (2011) proposed a new computational scheme in which CFD and MOC are coupled by modeling two pipe branches in CFD calculations, at the inlet and at the outlet of the PAT, and by imposing compatibility equations between CFD and MOC at extremes of the branches. A single pipeline system was analyzed. In the present research, due to the complexity case of study (WDN with private tanks) 1D model was used.

With the aim to combine water saving with current renewable energy policies and with the aim to reduce the pressure also when PATs are deactivated, the turbines are coupled with PRVs as shown in Figure 1.

The case study

The proposed numerical model has been applied on one of the 17 distribution networks of Palermo city (Sicily), called

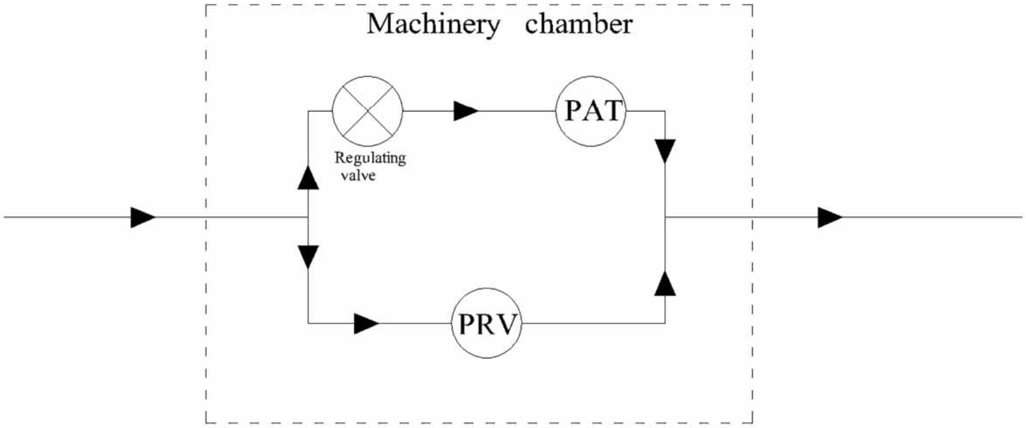

Figure 1 | Installation scheme of a coupled system of PAT and PRV.

Oreto-Stazione, designed to deliver about 400 L/capita/d but the actual mean consumption is about 260 L/capita/d that supply around 35,000 inhabitants (11,300 users). The network is made by HDPE (high density polyethylene) pipes and their diameters range between 110 and 400 mm. The network is fed through one cast-iron pipeline with a diameter of 500 mm and a length of 2,300 m connected, at the moment, to one reservoir, located at an elevation of 45 m slm, named 'San Ciro Basso' (see Figure 2). Additional details on the analyzed network can be found in De Marchis *et al.* (2010).

The current configuration of the network is characterized by significant inequality in the distribution of water resources during intermittent supply. As demonstrated by Freni *et al.* (2014), the WDN can be subdivided in two main regions by geodetic elevation. To improve the clarity, in Figure 2 the sub-network characterized by lowest elevation has been delimited through dotted lines, while the highest geodetic region is indicated through a continuous line. The network orography suggests the possibility to introduce some PATs in the network pipes connecting the two main regions.

The analyzed WDN is monitored by six pressure cells and two electromagnetic flow meters (Figure 2). The pressure data were used for model calibration and validation, showing the ability of the proposed hydraulic model to reproduce the behavior of a real network (see De Marchis *et al.* (2010, 2011) for the validation tests).

As shown in Figure 2, the two sub-zones are connected by mean of four main pipes (named p1–p4), one located close to the supply node, two located in a middle zone, while the third is about 1.5 km far from the inlet node. Several numerical simulations were carried out to evaluate the convenience of PAT installation.

One of the main problems in PAT positioning is to find the optimal installation point, thus to achieve the maximum energy production but ensuring water supply. In the framework of the network optimization, two main techniques can be applied. The former is guided by the HR. In the latter, PATs, as well as PRVs, can be placed using algorithms and techniques for water network partitioning and sectorization (WNPS) that allow the definition of optimal water networks partitioning, compatibly with the level of service required by the users (Di Nardo & Di Natale 2011;

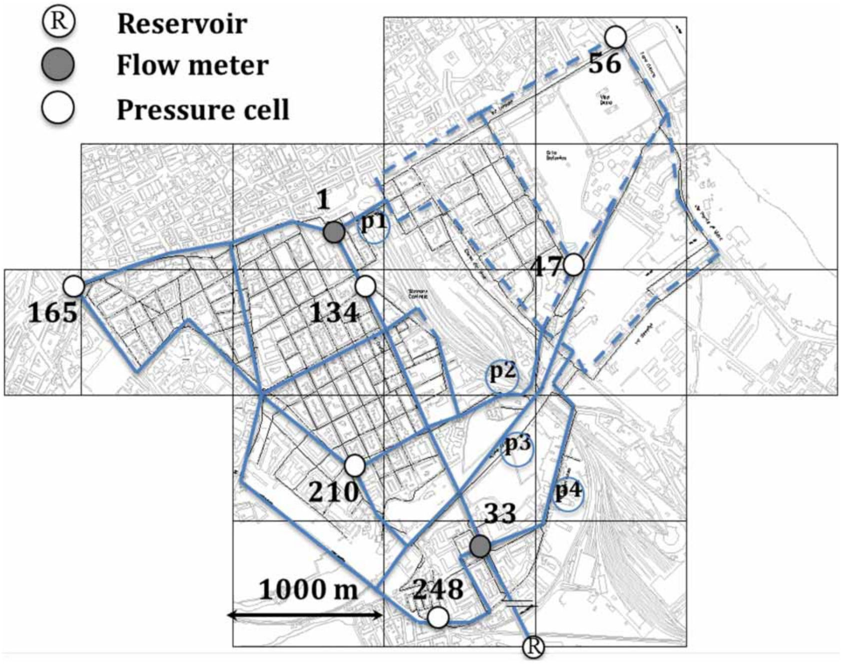

Figure 2 | Case study network Oreto-Stazione. The continuous blue/dark gray lines represent the main WDN in the region with the highest elevation; the dashed blue/dark gray lines represent the main WDN in the region with the lowest elevation. p1–p4 represents the four main pipes connecting the two main areas. The full color version of this figure is available online at http://www.iwaponline.com/jh/toc.htm.

Di Nardo *et al.* 2013a, b; Sharma & Swamee 2005). In small WDNs, the HR can be easily applied, achieving high performance level, while in large WDN the application of specific algorithm of partitioning should be suggested (Di Nardo *et al.* 2014).

Following the recent findings of Di Nardo *et al.* (2014), PATs' optimal position achieved through automatic WNPS should represent a good economic compromise between energy production and network management; the proposed methodologies, in fact, respects one of the criteria for system success proposed by Kroll & King (2010), the dual-use value.

In the present analysis, due to the small size of the network, the PAT position was guided by hydraulic expertise. To this aim a numerical simulation is initially performed without PAT, thus to analyze the water head in the nodes and discharges in the pipes.

The main idea is to investigate the energy recovery in the Oreto-Stazione WDN taking advantage of the high variation of the geodetic elevation between the two sub-networks. Specifically, five different installation points were analyzed.

PI1 In the first PAT installation case (hereafter referred to PI), the PAT has been installed in the pipe of the network, having a diameter of 150 mm, defined as pipe p1 in Figure 3(a).

PI2 The second scenario refers to the PAT installed in the connection pipe between the highest and lowest geodetic sub-zone, numbered p2 in Figure 3(b), having a diameter of 160 mm.

PI3 The third PAT station is located in the connection pipe p3 reported in Figure 3(c), characterized by a diameter of 110 mm.

PI4 In the fourth scenario PAT is installed in the pipe, linking the two sub-networks, far from the supply node, reported in Figure 3(d) as pipe p4. In this case the pipe diameter is 225 mm

PI5 In the last PAT installation case as shown in Figure 3(e), PAT has been collocated in the main pipe connecting the reservoir with the WDN, having a diameter of 500 mm.

The analyzed network, as briefly described above, is characterized by the presence of private tanks that strongly modify the network behavior. The local reservoirs, installed by the users to cover the water scarcity condition periods, can affect the energy production and the efficiency of PAT installation. In this framework, the proposed dynamic numerical model was applied to investigate on the effect of the user water tanks in the energy recovery from the WDS. All five scenarios were simulated both neglecting and taking into account the local tanks.

ANALYSIS OF RESULTS

The analysis here reported aimed to check the validity of the installation of PATs in real WDNs through numerical modeling. With the aim to reduce the cost of installation and maximize PAT efficiency, a numerical model able to guide the water managers should be very attractive. In the following, a preliminary analysis is discussed in light of the CPP, exploring five different positions of installation, as specified in the previous section. In the framework of energy recovery from the water distribution systems, the results of 10 different scenarios are presented. For each of the above presented PI, two sets of numerical simulations, applying a pressure driven model, were carried out. In the first one, the effects of the local water tank was neglected, while in the second set of numerical simulations the presence of private reservoirs was simulated according to the tank model given by Equations (12) and (13). In the first set of simulations, the numerical model was applied neglecting the unsteady filling process of the network and a steady state version of the MOC model was used. In this case the typical average daily user demand pattern was applied to simulate the node discharges. Specifically, demand pattern adopted by Puleo *et al.* (2013) was used. In contrast, the simulations carried out taking into account the private reservoirs were performed considering that all of the pipes in the network are initially empty, these empty pipelines are connected to the network reservoirs and the filling of the network starts after the opening of the gates. It is imposed that the power production starts 2 hours after the filling process starts.

The economic analysis has been carried out calculating the averaged daily energy production (ADEP (kWh/day)) integrating the PAT power profile along 24 hours, through

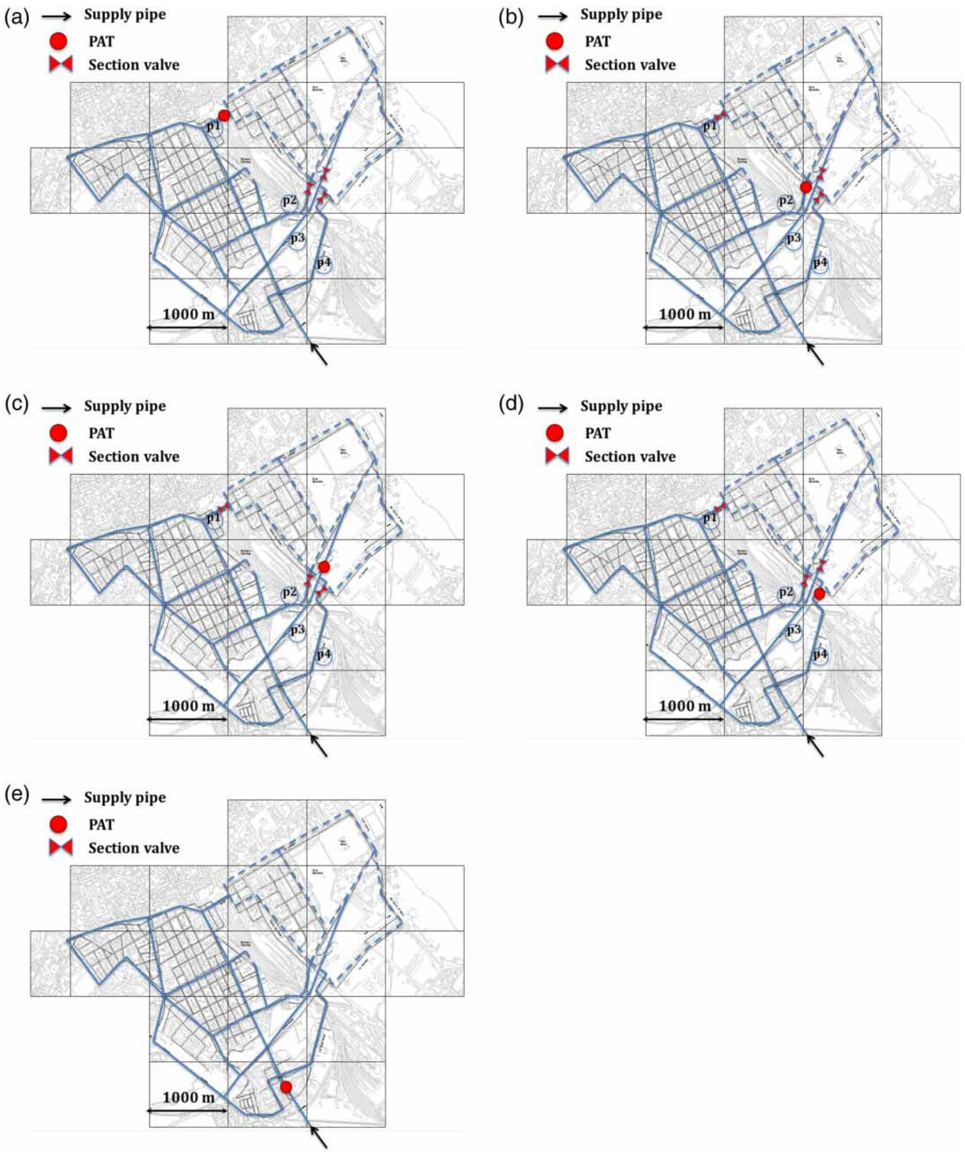

Figure 3 | Point of the PAT installation and closed pipes on network mains: PI1 (a), PI2 (b), PI3 (c), PI4 (d) and PI5 (e). The blue/dark gray continuous and dashed lines highlight the boundaries of the two main region of the network. The full color version of this figure is available online at http://www.iwaponline.com/jh/toc.htm.

the equation

$$\mathrm{ADEP} = \frac{1}{3600} \cdot \frac{\gamma}{1000} \int_T q \cdot \eta_t \cdot H_t \cdot dt \tag{16}$$

where $T = 86{,}400$ s, η_t is the PAT efficiency, γ is the specific weight of water, q the flow rate through the supply pipe and H_t the head drop due to the PAT, calculated according to Equations (12) and (13). Once the ADEP is calculated, the average yearly energy production (AYEP (kWh/year)) is calculated considering that the ADEP is generated every day. This hypothesis can be considered acceptable at least for the case study considered here, where a sub-network supplies mainly a resident population.

In light of the estimation of the annual revenue (AR (€/years)), AYEP is multiplied for the unit energy revenue, equal to 0.22 €/kWh (according to the average value for the renewable produced energy in Italy).

Finally, the economic analysis was carried out calculating the CPP through the equation

$$\mathrm{CPP} = \frac{\mathrm{EGE} + \mathrm{CW}}{\mathrm{AF}} \tag{17}$$

where EGE is the energy generation equipment, CW represents civil works cost, while AF is the annual financial saving (€/year). The EGE has been evaluated taking into account PAT cost, generator cost and related electrical equipment. PAT cost has been calculated according to the BEP of the power of PAT. Specifically, based on market analysis, the EGE cost has been estimated considering 2,000 euro/kW for each turbine power installed P_{inst}. The civil works cost is added too. According to Fontana *et al.* (2012), CW has been calculated considering 30% of the EGE costs.

Table 1 | Pumps as turbines characteristic in turbine mode

Scenario	**PI**	**Private tank**	**D_{imp} (mm)**	**Q_{BEP} (m^3/s)**	**H_{BEP} (m)**	**P_{BEP} (kW)**
TC1	PI1	N	160	0.030	8.90	2.00
TC2	PI2	N	160	0.030	8.90	2.00
TC3	PI3	N	160	0.025	12.80	2.40
TC4	PI4	N	200	0.030	8.70	1.92
TC5	PI5	N	500	0.080	6.00	3.00
TC6	PI1	Y	160	0.030	8.90	2.00
TC7	PI2	Y	160	0.030	8.90	2.00
TC8	PI3	Y	160	0.025	12.80	2.40
TC9	PI4	Y	200	0.030	8.70	1.92
TC10	PI5	Y	500	0.080	6.00	3.00

The AF is calculated as the difference between the annual revenue minus the maintain cost (MC). Following some recent literature findings, MC can be evaluated as 15% of the total cost of the PAT

$$\mathrm{AF} = \mathrm{AR} - \mathrm{MC} \quad \text{with} \quad \mathrm{MC} = 0.15(\mathrm{EGE} + \mathrm{CW}) \tag{18}$$

In Table 1 some details on the BEPs of the scenarios, used in Equations (12)–(15) of the PAT model, are reported.

In Table 2 the costs analysis and the CPP for all scenarios is reported. The PAT cost has been estimated from the PAT power installed P_{inst}, obtained as the product of the P_{tb} and the overall PAT efficiency η_t.

The results of the economic analysis show a general efficiency of the energy recovery, with an attractive payback period that reached approximately 2 years, in almost all cases. Similar CPP was obtained by Fontana *et al.* (2012). The worst result is achieved for scenario 8, characterized by a PAT set on PI3 and simulating the presence of the private water tanks. In this case, in fact, a very high payback period of about 14 years is verified. This result can be attributed to the small diameter of the pipe in PI3. On the other hand, the highest values of energy production and CPP are achieved when the pipe is installed in the supply pipe (TC5 and TC10 associated to the PI5, Figure 3(e)). This is attributed to highest discharge values and to the highest

Table 2 | Economic feasibility of pumps as turbines installation in a water distribution network: cost and capital payback period analysis

Scenario	**PI**	**Private tank**	**Pinst (kW)**	**ADEP (kWh/day)**	**AYEP (kWh/year)**	**EGE (€)**	**CW (€)**	**AR (€/year)**	**MC (€/year)**	**AF (€/year)**	**CPP (year)**
TC1	PI1	N	2.35	61.60	22,484.00	4,705.88	1,411.76	4,946.48	917.65	4,028.83	1.52
TC2	PI2	N	2.35	44.30	16,169.50	4,705.88	1,411.76	3,557.29	917.65	2,639.64	2.32
TC3	PI3	N	2.82	24.58	8,971.70	5,647.06	1,694.12	1,973.77	1,101.18	872.60	8.41
TC4	PI4	N	2.26	74.83	27,312.95	4,517.65	1,355.29	6,008.85	880.94	5,127.91	1.15
TC5	PI5	N	5.66	192.71	70,339.15	11,320.75	3,396.23	15,474.61	2,207.55	13,267.07	1.11
TC6	PI1	Y	2.35	38.12	13,913.80	4,705.88	1,411.76	3,061.04	917.65	2,143.39	2.85
TC7	PI2	Y	2.35	33.30	12,154.50	4,705.88	1,411.76	2,673.99	917.65	1,756.34	3.48
TC8	PI3	Y	2.82	19.91	7,267.15	5,647.06	1,694.12	1,598.77	1,101.18	497.60	14.75
TC9	PI4	Y	2.26	40.22	14,680.30	4,517.65	1,355.29	3,229.67	880.94	2,348.72	2.50
TC10	PI5	Y	5.66	89.10	32,521.50	11,320.75	3,396.23	7,154.73	2,207.55	4,947.18	2.97

value of head drop in the PAT. This last result is in agreement with the recent finding of Carravetta *et al.* (2013b), obtaining similar numerical simulations in the same case study. In Figure 4 the CPP, summarized in Table 2, is plotted with the AR.

Focusing on the effect of the private tanks on renewable energy production, it is clear that in all cases analyzed the effect of local reservoir is a high reduction of energy production. This reduction can be well observed in Figure 5 where the energy production time series is plotted.

Figure 5(a) shows the power production achieved when the private tanks are neglected. The variation of the power production profiles along 24 hours follows the typical average daily user demand pattern applied in the numerical simulation. The minimum energy production is verified, in all cases, at 5:00 a.m., corresponding to the minimum value of user demand. In the first set of simulations, carried out neglecting the private reservoirs, the numerical simulations were performed reproducing a continuous supply, thus the steady state model was considered. On the contrary, when the water reservoirs are simulated, the unsteady filling process was considered. The choice is justified bearing in mind that the reservoirs find a direct utility in WDN characterized by intermittent distribution. In Figure 5(b), the PAT production, considering the user tanks, is plotted. The energy production is accounted for 2 hours from start of the simulation. Overall, Figure 5(b) shows the effect of the reservoirs in reduction of energy production in time. The decrease can be attributed to the water tank model (Equations (10) and (11)) adopted in the simulation. Specifically, when the reservoir water level H_j reaches the maximum allowed water level in the tank $H_{j,\max}$, applying Equation (12), the supply is closed. The closure of the emitter in the private tanks causes a reduction of the flow discharge in the WDN, leading to a progressive reduction of power production, especially in the last hours, where almost all tanks all fill with fluids. As shown in Table 2, this reduction causes an increase of the CPP. The

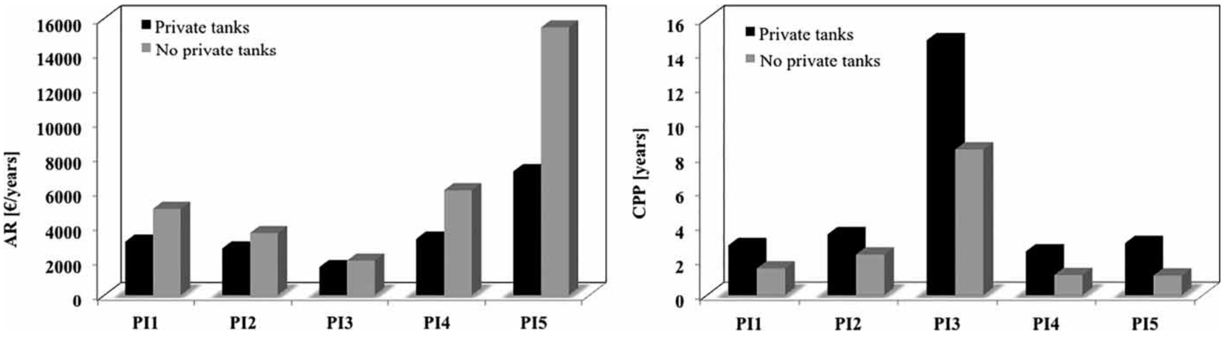

Figure 4 | Comparison between the CPP and AR obtained simulating the presence of the private tanks used by the users and neglecting them.

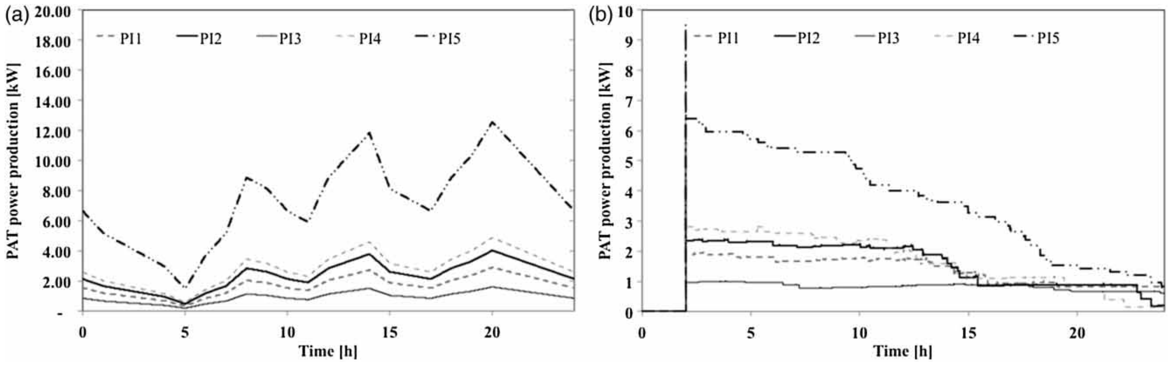

Figure 5 | PAT power production profiles along 24 hours. (a) Production obtained simulating the WDN without the user's reservoir. (b) Production obtained simulating the WDN taking into account for the user's reservoir.

comparison between the power production obtained simulating the water tanks and neglecting them clearly shows the overall effect of the private tanks to reduce the energy production.

To better investigate on tank effect, the annual financial saving AF is plotted in Figure 6. Specifically, AF, achieved for different scenarios, are analyzed in light of the total installation cost, calculated by adding the EGE to the CW. The figure confirms that, at least in the present case, private reservoirs cause a reduction of performance of energy recovery in WDNs.

The obtained results clearly show that in some cases the use of PATs to recover energy from the WDN is a very attractive solution, reducing the energy consumption in the network and giving economic benefits. Despite this, our analysis showed that, in order to maximize PAT efficiency in terms of economic feasibility, it is essential to choose the optimal point of installation. In some cases, in fact, see for example the PI3 proposed in our numerical simulations, the energy production as well as the annual financial savings are very low and give rise to payback periods greater than 10 years. In this framework, the proposed model should be an interesting tool aimed at supporting the water utilities to check the possible economic advantage to install PATs in their specific network.

The use of PATs causes a pressure reduction similar to the effect of PRVs (Freni *et al.* 2014). The pressure reduction has two main folds: the first is the well-known reduction of leakages in WDN. Conversely, in head-driven intermittent WDN, the reduction of the pressure can increase the inequities among the users. It is fundamental, thus, to analyze PAT production in light of the water volume supplied to the users. Specifically, in the present research, the energy production was tuned in such a way to maintain the user's satisfaction achieved in absence of PATs. To this aim, two further simulations have been carried out simulating the dynamic behavior of the WDN in the absence of PATs (here after referred to as PI0) and calculating the water head and water volume supplied at each node.

In Figure 7, the water head at each node for all cases is reported. Specifically, Figure 7(a) shows the water head elevation, at the end of the simulation ($T = 86{,}400$ s), achieved in all nodes of the skeletonized network eliminating the private tanks. In Figure 7(b), conversely, the head elevation, at the end of the simulation ($T = 86{,}400$ s), simulating the effect of local reservoirs, is plotted. The comparison between the piezometric profiles obtained in the scenarios PI0 and PI5, shows a constant shift of the head in all nodes when the PAT is located in the main supply pipe (see Figure 3(e)).

The analysis of the other scenarios shows that PATs cut the pressure in the WDN in the region characterized by the lowest geodetic quotes (nodes 16–40), while in the upper part of the network very few variations are observed. The downward shift of the pressure is coherent with the head

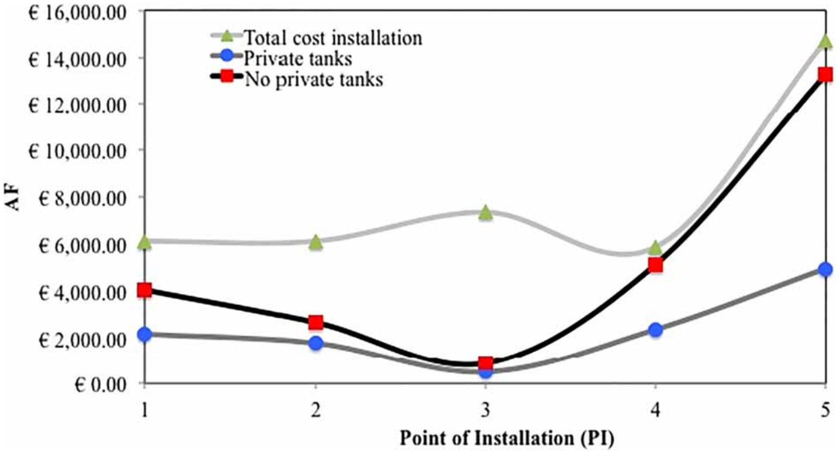

Figure 6 | Annual financial saving obtained simulating the presence of the private tanks used by the users and neglecting them. The total cost of installation (CF + EGE) is plotted for reference.

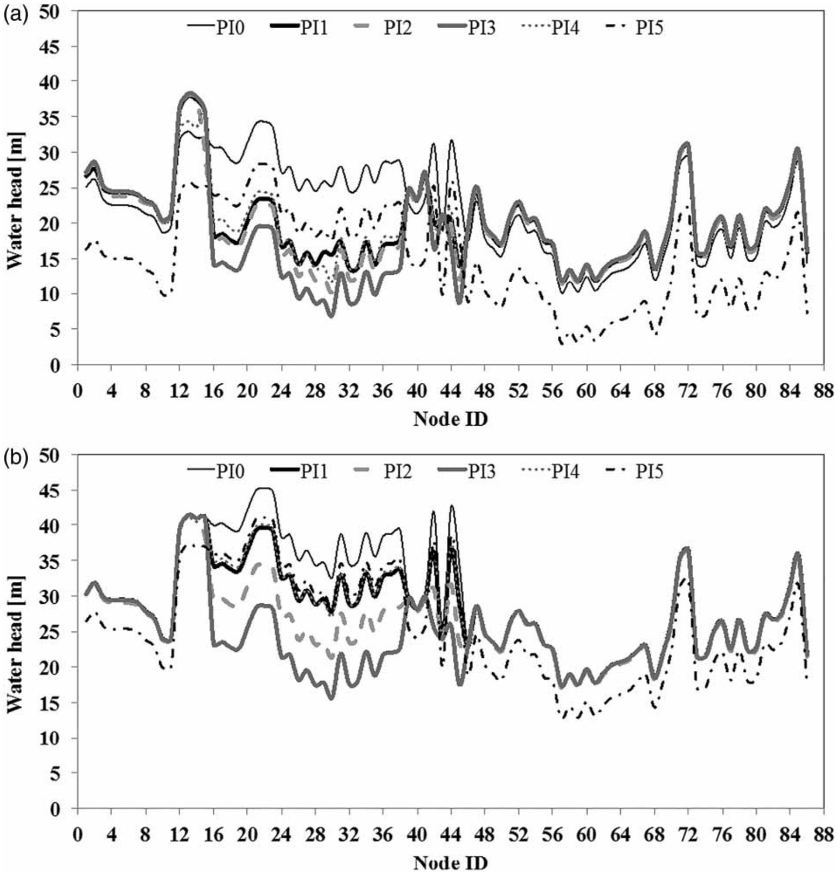

Figure 7 | Comparison of the water head elevation in all nodes of the WDN for all scenarios. (a) WDN without the user's reservoir. (b) WDN with the user's reservoir. The case PI0, referred to the simulation of WDN without PAT, is added for reference.

drop *Ht* inside the PAT. It is worthwhile to notice that, in both cases, the maximum pressure reduction is verified for the scenario PI3, where the minimum energy production occurs and the analysis of the payback period reveals a very low economic benefit. The results shown in Figure 7, achieved also in other time periods, thus can be generalized for all 24 hours.

In head-driven models, water volume supplied is directly correlated to the pressure, thus a high pressure cut could lead to an increase of inequities among the users. To investigate this issue, the water volume supplied in each scenario here considered has been compared with the water volume supplied in the case without PAT (PI0). The percentage of the total water volume not supplied in the WDN is thus reported in Figure 8. Coherently with the results presented above, it can be seen in the figure that the PI3 test causes a peak of water volume reduction. In the other scenarios,

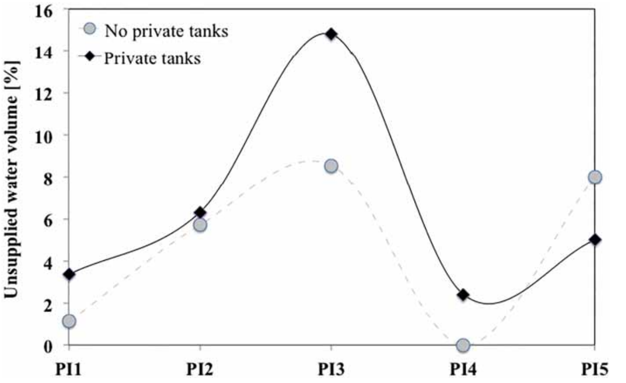

Figure 8 | Analysis of percentage of the water volume unsupplied to the users in the different scenario.

on the other hand, the water volume supplied is quite similar to the PI0 scenario and the slight differences can be reasonably accepted, considering the fact that the network was designed to supply about 400 L/capita/d, but the actual average consumption is about 260 L/capita/d (see De Marchis *et al.* 2011).

Furthermore, the slight reduction of the water volume supplied should be reduced by applying two or more PATs working alternatively. Some analysis is focusing on this issue, thus to maximize PAT efficiency and reduce the inequities in the water resource.

The present analysis showed that PAT installation can be considered strategic in terms of renewable energy production and that the proposed numerical model should be a powerful tool able to guide the water utilities in the best positioning of the PAT to maximize their efficiency.

CONCLUSIONS

In the study, PATs are analyzed in terms of energy and capital cost recovery. A complex WDN was analyzed considering different installation points and two different supply conditions: intermittent and continuous. PAT installation nodes were chosen using a hydraulic criterion; nevertheless, efforts have to be carried out in order to apply district sectorization tools to optimize the choice of insertion points for PAT and gate valves.

A numerical dynamic model of the PAT was integrated with the network model including private tanks. The model was shown to be robust and to correctly represent energy recovery and water supply modification.

The analysis showed that the use of PATs can be attractive in economic terms considering the lower capital cost, if compared with traditional turbines, and energy recovery. The CPP is strongly dependent on installation point inside the network and it is ranging between 1 and 3 years in the best cases; at the same time, if the installation point is wrong, the CPP can raise to 14–15 years, making the investment economically unfeasible.

The results obtained showed that the presence of reservoirs causes a high decrease of energy production, achieving a reduction of about 50%. Despite this, due to the low PAT equipment costs, the numerical analysis showed that, optimizing the selection of the points of installation, PATs can be considered a real attractive energy recovery device for WDNs.

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