Pumps as turbines (PATs) in water distribution networks affected by intermittent service

Valeria Puleo, Chiara Maria Fontanazza, Vincenza Notaro, Mauro De Marchis, Gabriele Freni and Goffredo La Loggia

ABSTRACT

A hydraulic model was developed in order to evaluate the potential energy recovery from the use of centrifugal pumps as turbines (PATs) in a water distribution network characterized by the presence of private tanks. The model integrates the Global Gradient Algorithm (GGA), with a pressure-driven model that permits a more realistic representation of the influence on the network behaviour of the private tanks filling and emptying. The model was applied to a real case study: a District Metered Area in Palermo (Italy). Three different scenarios were analysed and compared with a baseline scenario (Scenario 0 – no PAT installed) to identify the system configuration with added PATs that permits the maximal energy recovery without penalizing the hydraulic network performance. In scenarios involving PAT on service connections, the specification of PAT operational parameters was also evaluated by means of Monte Carlo Analysis. The centralized solution with a PAT installed downstream of the inlet node of the analysed district, combined with local PATs on the larger service connections, proves to be the most energy-efficient scenario.

Key words | energy production, hydraulic modelling, pressure-driven demand, pump as turbine, water distribution networks

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INTRODUCTION

In recent years there has been increasing attention given to energy costs associated with the operation of water distribution networks (WDNs), leading to the development of management strategies aimed at reducing net energy consumption.

The reconfiguration of water supply systems (WSSs) to produce energy is a favourable solution because most of the system components already exist (e.g. reservoirs, pipes, valves) and there is a near-guaranteed continuous flow in the system along each day (Vieira & Ramos 2008). In transmission pipelines, where the available hydraulic power is considerable and fairly constant, the conventional hydraulic turbine installation is a suitable solution. Conversely, where the flow rates and heads vary, the application of these devices may be not cost effective and other equipment may have to be investigated. Ramos *et al.* (2009) analysed different energy converters for potential implementation in WSSs or in other water pipe infrastructures, such as irrigation, wastewater or drainage systems, through an extensive comparison between simulations and experimental tests. For each energy converter, the range of application was obtained: demonstrating that such devices are able to deliver power outputs from about 28 W to 40 kW for small heads (0.6–20 m) and discharges ranging between 0.006 and 2 m^3/s.

One of the easiest ways to reduce the cost connected with the installation of common turbines is the use of a centrifugal pump in reverse mode (Ramos & Borga 1999). Compared to other hydraulic power recovery turbines, pumps as turbines (PATs) do not require complicated and expensive control systems (Nautiyal & Anoop Kumar

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2010). In the literature, several applications in off-grid and standalone power plants have been proposed (Arriaga 2010), and recently the use of such devices has been suggested for energy production in WSSs.

Ramos *et al.* (2010) carried out an experimental investigation to analyse and compare hydraulic-system response under steady- and transient-state conditions using a real pressure-reducing valve (PRV) and PAT. Different values of discharges and upstream heads were tested in the laboratory and the pressure drop owing to both devices was shown to be quite similar. Moreover, an optimal solution regarding the valve opening adjustment and the selection of the best characteristic curve of the PAT was identified by coupling a genetic algorithm technique and the EPANET hydraulic simulator. For the related case study, Ramos *et al.* (2010) found that the PAT's pay-back can be achieved in around 3 years while the total investment is paid back in around 9 years. The aim of this analysis was to demonstrate that PAT and micro-turbines can be alternative solutions to control network pressure as well as producing energy in a cost-effective fashion. Fontana *et al.* (2012) presented a simulation model coupled with genetic algorithms to assess the optimal location of PRVs for reducing losses and in a subsequent phase of analysis, some or all of the valves were replaced by PATs for energy recovery. The authors noticed that water loss reduction, according to the optimal location of PRV, does not fulfil the maximum energy production potential. Furthermore, the experimental results showed that PATs do not allow fine regulation of the head drop, but that adequate pressure service was still maintained.

As pointed out by several authors (Williams 1994, 1996; Derakhshan & Nourbakhsh 2008a,b; Singh & Nestmann 2011; Yang *et al.* 2012), one of the most important limitations of PAT applicability is related to evaluation of the characteristic curves of the pump in reverse operation. Therefore, establishing a correlation enabling the passage from the 'pump' characteristics to the 'turbine' characteristics is the principal challenge in using a pump as a turbine. Many researchers have presented theoretical and empirical relations for predicting the PAT characteristics at the Best Efficiency Point (BEP). A good literature review has been provided by Nautiyal & Anoop Kumar (2010). Unfortunately, the results predicted by these methods are not reliable for all pumps with different specific speeds and capacities. Moreover, the implementation of the analytical procedure is difficult due to the requirement for very detailed data, some of which is patented and available only to the manufacturers (Singh & Nestmann 2010). Most recent attempts to predict performance of PATs have been made using Computational Fluid Dynamics (CFD) (Carravetta *et al.* 2012; Yang *et al.* 2012). The PAT behaviour is very complex and it is difficult to find a simple relationship to cover the behaviour of all pumps in reverse mode. Generally, it has been observed that if the PAT works at other than design flow, a relatively rapid drop in efficiency will be seen. Poor performance, then, is often linked to an inappropriate selection of equipment.

In urban areas, the discontinuous flow rates related to user demand may prevent the PAT from producing continuous and profitable energy. In Carravetta *et al.* (2012), an interesting PAT design method based on a Variable Operating Strategy was proposed in order to predict the PAT behaviour and to find the optimal solution which maximizes the energy produced under variable operating conditions. Nevertheless, the limitation linked to the discontinuous flow rates could be partially overcome in contexts where intermittent water distribution was a common issue and users installed private tanks to mitigate its impact. Network performance and the accessibility of water resources to users are highly affected by the presence of private tanks (Fontanazza *et al.* 2007; De Marchis *et al.* 2010, 2011). User demand depends on the filling and the emptying process of the private tanks and this fact may significantly improve PAT performance.

This paper analyses the potential energy recovery obtained through the use of PAT devices installed in a WDN with private tanks (Fontanazza *et al.* 2012). To this aim, a numerical hydraulic model, integrating the Global Gradient Algorithm (GGA) (Todini 2003; Giustolisi *et al.* 2008) with a pressure-driven model (Criminisi *et al.* 2009) was developed. This model is able to simulate the presence of private tanks and their filling/emptying process and to simulate the presence of PATs either in the service connections or in the mains network pipes. The mathematical model was applied to a real case study: a District Metered Area (DMA) in Palermo (Italy).

METHODOLOGY

At the time of writing, many commercial and open-source software packages are available to perform the hydraulic modelling and analysis of a WDN. Several solvers compute the hydraulic steady-state variables such as pipe water flow and nodal head by means of the Hardy–Cross or Newton–Raphson techniques. Sophisticated analyses can be undertaken by hydraulic solvers such as pipe roughness calibration, leak detection, water quality analysis and assessment of pumping energy consumption or planning rehabilitation/maintenance practices (Berardi *et al.* 2010).

This paper introduces a numerical model that integrates the GGA formulated by Todini (2003) and recently improved by Giustolisi *et al.* (2008) with a tank node model (Criminisi *et al.* 2009), that permits a more realistic representation of the influence on the network behaviour of the private tanks filling and emptying and the presence of PATs. The system was simulated in quasi-steady-state conditions, i.e. considering steady-state conditions at each time step with variable boundary conditions and water demands.

Demand–pressure relationship and the tank model

The filling of private tanks and the access of users to water supply greatly depends on the network pressure levels. In traditional demand-driven analysis, network modelling is carried out by assigning the specific water demands for nodes and computing the nodal pressure heads and link flows from the equations of mass balance and pipe-friction head loss. In real networks, this simple, widely adopted approach can yield nodal pressures that are lower than the minimum required service level or which even become negative: in this condition, design demands cannot be met. Although this is a well-known problem and has been tackled by many researchers (Bhave 1981; Germanopoulos 1985; Wagner *et al.* 1988; Reddy & Elango 1989; Chandapillai 1991; Gupta & Bhave 1996; Fontanazza *et al.* 2007), it is sometimes still ignored. Since the 1980s, various methods, generally named pressure-driven analysis, have been proposed to compute actual water consumptions, network node pressures and flows involving an assumption of the relationship between pressure and outflow at the demand nodes. Furthermore, some questions are still unresolved: especially regarding the definition of the relationship between supplied water volumes and available network pressure.

The method introduced by Reddy & Elango (1989) is wholly different from the others: the pressure–consumption function does not have an upper bound and the node outflow is the maximum taken by the network, only related to the available nodal pressure:

$$q_{\mathrm{up}} = k \cdot (P - P_{\mathrm{min}})^h \tag{1}$$

where q_{up} is the actual node outflow, P is the node pressure, P_{min} is the minimum pressure required to have outflow at the node, k and h are calibration coefficients.

Where water distribution is periodically supplied on an intermittent basis, users often modify their internal water system in order to introduce private tanks with pumps to collect as much water as possible – even if the available pressure is lower than minimum required to have tank inflow. In such situations, the method proposed by Reddy & Elango (1989) has to be modified to take into account the presence of tanks and float valves that progressively reduce inflow volume while the tank is filling (Criminisi *et al.* 2009). Thus the demand–pressure relationship $q = f(P)$ at each demand node in the network is based on the combination of the tank continuity equation (Equation (2)) and the float valve emitter law (Equation (3)):

$$q_{\mathrm{act}} - D = \frac{\mathrm{d}V}{\mathrm{d}t} = A\,\frac{\mathrm{d}h}{\mathrm{d}t} \tag{2}$$

$$q_{\mathrm{act}} = C_v \cdot a_v \cdot \sqrt{2gP} \tag{3}$$

where q_{act} and D are the inflow from the distribution network to the private tank [m^3/s] and the user water demand downstream of the tank [m^3/s], respectively; V is the volume of the storage tank [m^3] having area A [m^2] and variable water depth h [m]; C_v is the float valve emitter coefficient [–], a_v is the valve effective discharge area [m^2], P is the available pressure from the distribution network [m], and g is the acceleration due to gravity [$\mathrm{m/s}^2$]. More details about the model and its calibration can be found in the referenced literature. For the temporal discretization of the continuity equation (Equation (2)) the first-order Euler method is used. For each node the boundary conditions related to user demand are known and the tank initial volumes are selected according to a random distribution in the range of 10–100% of the maximum storage volume. In this paper, the formulation presented in Criminisi *et al.* (2009) was used and slightly modified: an upper bound is introduced beyond which the tank inflow is considered constant and pressure independent, in order to take into account the fact that local head losses in the service connections greatly increase as flow rates rise.

PAT characteristic curve

As mentioned above, the model simulates the presence of PATs both in the service connections and in the main pipes of the WDN. Modelling of the PATs was undertaken, considering their characteristic curves. Some experimental studies have been presented in the literature to estimate the characteristic curves of PATs. However, some questions still remain, especially regarding the repeatability of prediction accuracy with respect to pumps of different designs and manufacturers (Singh & Nestmann 2010). Derakhshan & Nourbakhsh (2008a, b) developed a new method for finding out the BEP of a PAT based on the pump's hydraulic specification. Some correlations were also presented for pumps with different impeller diameters but same specific speeds. The authors illustrated a comparison between different methods for finding out the BEP of a PAT. In addition to this, some relations were presented for determining the complete characteristic curve of a PAT based on its BEP. As suggest by Carravetta *et al.* (2012), once the prototype characteristic and efficiency curve are available, the results may be extended to obtain the characteristic curves of other similar devices of different runner diameters and rotation speeds by using the Suter parameters (Wylie *et al.* 1993).

In the present study, several manufacturers' catalogues were investigated to identify pumps satisfying the given turbine operating conditions (head and flow) and the characteristic curves provided by Derakhshan & Nourbakhsh (2008a, b) were assumed to be applicable to the analysis. Namely they showed head number (ψ) and discharge number (ϕ) curves, from lower to higher specific speeds. The discharge number $\phi = Q_{\text{pat}}/(n_s \cdot D_{\text{imp}}^3)$ and the head number $\psi = g \cdot \Delta H_{\text{pat}}/(n_s^2 \cdot D_{\text{imp}}^2)$ are dimensionless parameters depending on the rotational speed n_s[rps] and on the impeller diameter D_{imp} [m], g is the acceleration due to gravity [m/s^2], ΔH_{pat} [m] and Q [m^3/s] are head and flow rate through the device, respectively. Several characteristic curves can be obtained by varying the rotational speed n_s and the impeller diameter D_{imp}. Knowing the diameter D_{imp}. the actual flow through the PAT, Q, and the available water head, ΔH_{pat} the rotational speed, n_s, can be calculated at each model time step thus obtaining all of the PAT characteristic parameters. The resulting values can be reported and interpolated, i.e. with second order polynomials or above depending on the desired level of approximation. In the present study the characteristic curves are interpolated using Equation (4):

$$\Delta H_{\text{pat}} = a \cdot Q_{\text{pat}}^2 + b \cdot Q_{\text{pat}} + c \tag{4}$$

where *a, b* and *c* are the coefficients of the quadratic function that represents the maximum efficiency condition, i.e. the operation of the PAT providing the highest energy efficiency. Given the average operating condition at the service connection and/or at the main pipe, it is possible to select a characteristic curve that is able to reduce pressure to an acceptable value and to produce energy at the same time. The values of the coefficients adopted in the analysis and the approximation errors are provided below.

Each PAT may be regulated (principally through changing its rotational speed) and its curves will change accordingly – even if this is usually associated with a reduction in energy production efficiency. This control is relevant particularly when PATs are installed on service connections because they will experience widely variable flows and their duty point will change significantly during the day. In such cases, an optimal regulation for a PAT should take into account the complete daily duty cycle and not solely the average conditions.

Global Gradient Algorithm (GGA)

Assuming Todini's formulation in matrix form (Todini 2003) for the steady-state simulation model, the problem can be formulated as follows:

$$\begin{bmatrix} A_{\mathrm{pp}} & A_{\mathrm{pn}} \\ A_{\mathrm{np}} & A_{\mathrm{nn}} \end{bmatrix} \begin{bmatrix} Q \\ H \end{bmatrix} = \begin{bmatrix} -A_{\mathrm{p0}} \cdot H_0 \\ 0 \end{bmatrix} \tag{5}$$

where $Q = [n_{\mathrm{p}}, 1]$ is a column vector of n_{p} unknown pipes flow rates; $H = [n_{\mathrm{n}}, 1]$ is a column vector of n_{n} unknown nodal heads; $H_0 = [n_0, 1]$ is a column vector of n_0 known nodal heads. $A_{\mathrm{nn}} = [n_{\mathrm{n}}, n_{\mathrm{n}}]$ is a diagonal matrix that contains the pressure-driven demands and $A_{\mathrm{pn}} = A^T_{\mathrm{np}}$ and A_{p0} are topological incidence sub-matrices of size $[n_{\mathrm{p}}, n_{\mathrm{n}}]$ and $[n_{\mathrm{p}}, n_0]$ respectively, derived from the general topological matrix $\overline{A}_{\mathrm{pn}} = [A_{\mathrm{pp}}|A_{\mathrm{p0}}]$ of size $[n_{\mathrm{p}}, n_{\mathrm{n}} + n_0]$.

In Equation (5), $A_{\mathrm{pp}} = [n_{\mathrm{p}}, n_{\mathrm{p}}]$ is a diagonal matrix whose elements, considering the PAT installation on the pipes, are defined, for $j = 1,\ldots,n_{\mathrm{p}}$, as:

$$A_{\mathrm{pp}}(j, j) = R_j\,|Q_j|^{n-1} + 2a_j|Q_j| - b_j \tag{6}$$

where R_j is the head loss coefficient, which is a function of a pipe's roughness, diameter and length, and n is the exponent which takes into account the flow regime and the head loss relationship employed; a_j and b_j are the coefficients of the PAT characteristic curve (Equation (4)) related to the jth pipe. To estimate the head losses for turbulent flow in rough pipes, the Sonnad and Goudar formulation was used (Sonnad & Goudar 2007).

The elements of the diagonal matrix A_{nn}, equal to the pressure-driven nodal demands, can be defined by the different formulations described in the previous paragraphs. Accordingly, for the $q = f(P)$ relationship, the following formulation will be used here:

$$q_{\mathrm{act}-i} = \begin{cases} q_{s-i} & \text{for } P_i > P_{s-i} \\ C_{vi} \cdot a_{vi} \cdot \sqrt{2gP_i} & \text{for } P_{\min-i} \le P_i \le P_{s-i} \\ 0 & \text{for } P_i < P_{\min-i} \end{cases} \tag{7}$$

where P_{s-i} is the reference pressure: if the pressure is above this threshold, a junction demand is not affected by pressure and it is considered to have a fixed flow rate q_{s-i}; $[P_{s-i}, P_{\min-i}]$ is the range for the intermediate operating condition when the actual demand is given as $q_{\mathrm{act}-i}$. $P_{\min-i}$ is the minimum pressure required to have outflow into the tank, if a PAT installation is carried out at the node, the $P_{\min-i}$ value varies accordingly to take into account the head loss due to the device.

The solution of the system shown in Equation (5), in accord with Todini (2003), is as follows:

$$\begin{cases} A^\tau = A_{\mathrm{np}}\left(D^\tau_{\mathrm{pp}}\right)^{-1} A_{\mathrm{pn}} - D^\tau_{\mathrm{nn}} \\ F^\tau = \left[A_{\mathrm{np}}Q^\tau - q^\tau_{\mathrm{act}}\right] - A_{\mathrm{np}}(D^\tau_{\mathrm{pp}})^{-1}(A_{\mathrm{p0}}H_0 + A^\tau_{\mathrm{pp}}Q^\tau + c) + \\ \quad -D^\tau_{\mathrm{nn}}H^\tau \\ H^{\tau+1} = (A^\tau)^{-1}F^\tau \\ Q^{\tau+1} = Q^\tau - (D^\tau_{\mathrm{pp}})^{-1}(A^\tau_{\mathrm{pp}}Q^\tau + A_{\mathrm{pn}}H^{\tau+1} + A_{\mathrm{p0}}H_0) \end{cases} \tag{8}$$

where τ is the iteration number and $\mathrm{D}_{\mathrm{nn}} = [n_{\mathrm{n}}, n_{\mathrm{n}}]$ and $\mathrm{D}_{\mathrm{pp}} = [n_{\mathrm{p}}, n_{\mathrm{p}}]$ diagonal matrices, whose elements denote derivatives of $q_{\mathrm{act}-i}$ and $R_j|Q_j|^{n-1}$ with respect to nodal pressure and pipe flow, respectively; c is a column vector of PAT coefficients. The problem is reduced to the inversion of a symmetrical and sparse matrix.

Unfortunately, as identified by Giustolisi et al. (2008), the pressure-driven formulation for $q_{\mathrm{act}-i}$ reduces convergence in the Newton–Raphson-based algorithms. In fact, the lack of convergence and the need to select a good starting point in Equation (8) are the most commonly encountered problems. To overcome the lack of convergence, the following equations were added to the formulation:

$$\begin{aligned} H^{\tau+1} &= \lambda^\tau \cdot \left(H^{\tau+1} - H^\tau\right) + H^\tau \\ Q^{\tau+1} &= \lambda^\tau \cdot \left(Q^{\tau+1} - Q^\tau\right) + Q^\tau \end{aligned} \tag{9}$$

where λ^τ, ranging between [0, 1], is an under-relaxation factor to accelerate the solution convergence for a non-linear hydraulic problem. The under-relaxation factor depends on the progress of the iterations. As the iterations converge, λ^τ approaches unity. The relation between lambda and convergence is governed by the mean of squared errors in the mass and energy balance equations while performing the iterative search. When any of these errors increases, the value of λ^τ is reduced by a factor (set equal to 0.7 here). When both errors decrease, the value of λ^τ is increased by a factor (set here equal to 1.5). The maximum number of iterations is also applied as a further control threshold (set here equal to 100).

To select a starting point, the values of $H^{\tau=0}$ and $Q^{\tau=0}$ have been chosen as follows:

$$H^{\tau=0} = P_{\min} + c_0 \cdot (P_s - P_{\min}) + Z \tag{10}$$

$$Q^{\tau=0} = \mathrm{pinv}(A_{\mathrm{np}}) \cdot q_{\mathrm{act}}^{\tau=0} \tag{11}$$

where Z is the vector of nodal elevations; P_s and $P_{\min}$ are vectors whose elements are P_{s-i} and $P_{\min-i}$, respectively, and pinv(A_{np}) is the Moore–Penrose pseudo-inverse of A_{np} (a mathematical description reported in Giustolisi *et al.* (2008)); c_0 is a constant whose value ranges between 0 and 1.

CASE STUDY

The proposed model was tested on a small DMA of the distribution system of Palermo, Italy (Figure 1). The WDN of Palermo is divided into 17 sub-networks supplying, in total, around 900,000 users. The newest sub-networks (six) are constructed of high-density polyethylene (HDPE) pipes, the others being of different materials (principally steel and cast iron). Each sub-network is supplied by two different reservoirs. In this way, the pressure level on the sub-network is relatively flat. The case study analysed is a part of one of the new sub-networks and was chosen because it serves only residential users and is supplied by a single pipe from the main network.

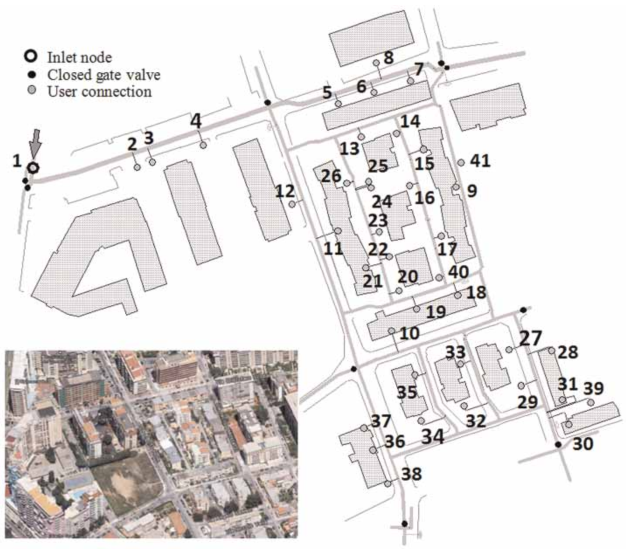

Figure 1 | The District Metered Area: a schematic depiction of the network.

The network of the DMA is about 1.3 km long and the pipes are made of polyethylene with diameters ranging between 110 and 225 mm. The 40 service connections supply a total of 164 residential end-users. The network was intermittently operated on a daily basis but it was continuously supplied during the analysis period. Actually, users are not supplied for a part of the day because the pressure is not sufficient and the local tanks are emptied to supply the users. Tanks are filled again in the periods of the day characterized by higher pressures. Downstream of the revenue water meter, local tanks were installed by single users and condominiums to compensate for supply interruptions. Currently, network pressure drops drastically during the day, precluding the supply of residential tanks on the rooftops.

Five service connections (nodes 2, 3, 4, 12 and 41) supply five condominiums with private tanks located below street level, while 35 service connections supply users with private tanks located on the roofs of the buildings.

At the end of 2009, a field trial was carried out in the DMA for 1 week. The input volume and pressure of the system at node 1 were measured with a temporal resolution of 30 minutes. Figure 2 shows, respectively, the daily average inflow (Figure 2(a)) and the nodal head H0 (Figure 2(b)) at the inlet node (node 1) obtained by averaging the related time series values measured during the trial.

Peak flows are registered at the beginning of the service day to fill the local tanks; after 8 a.m., all tanks are approximately full and inflows to the tanks are mainly due to users' consumption; in these conditions, users' water demand is much lower than during the tank filling period, thus increasing network pressure. Five domestic users were continuously monitored and average user-demand patterns were obtained from such users (Figure 3); these results were used for all similar users. To this end, a class C flow meter was coupled to a data logger recording volume data at 1-minute intervals and installed downstream of the private tank of each monitored user. The field trial results were used to calibrate the proposed model.

The model calibration was carried out against pressures metered near service nodes 7 and 30. Pressures were

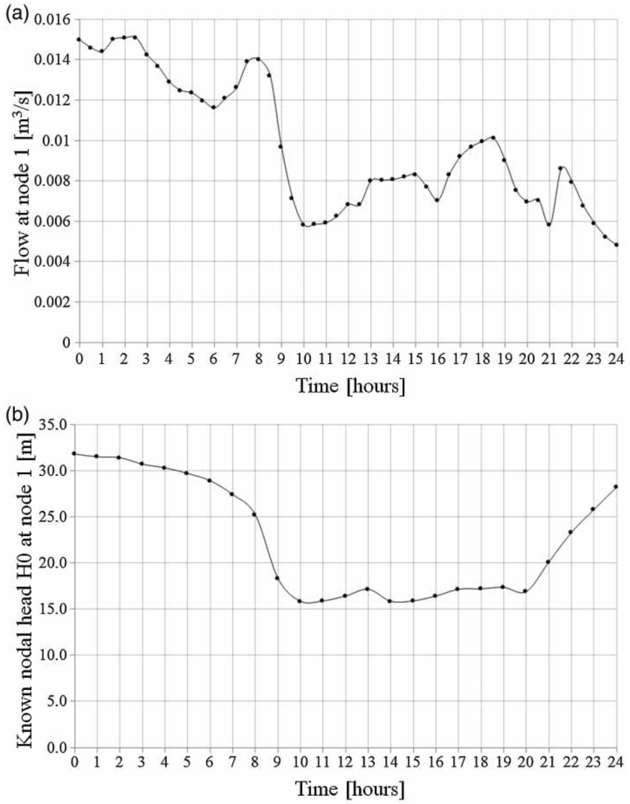

Figure 2 | (a) Daily pattern for inflow and (b) nodal head H0 at the inlet node (node 1) adopted in the DMA simulations.

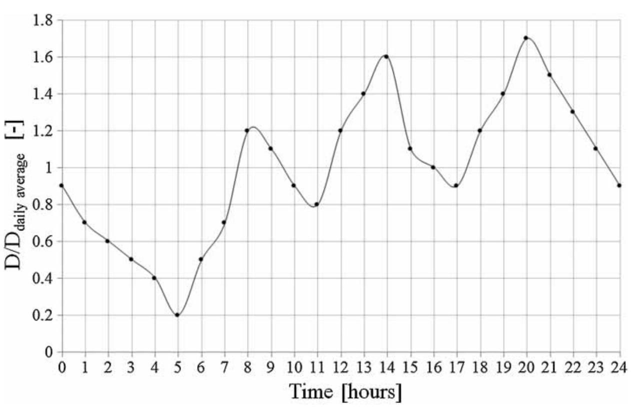

Figure 3 | Average daily user demand pattern adopted in the DMA simulations.

collected at 30-minute intervals over the entire monitoring period (7 days). Pipe roughness and C_v coefficients were calibrated: only one roughness value was considered for the whole network and two values of C_v were used for the condominium users and the residential users, respectively. Pipe roughness was calibrated to 0.008 on Manning's scale and coefficient C_v was set to 0.57 for residential users and 0.61 for the condos. Root Square Mean Error on monitored pressure after calibration was equal to 0.321 and 0.258 for node 7 and node 30, respectively, equivalent to an average absolute error of 4.3% on node 7 and 4.1% on node 30.

Analysed scenarios

In the present paper, three different scenarios were analysed and compared with the actual scenario (Scenario 0 – no PAT installed) to identify the most suitable solution. Scenario 1 simulates the presence of PAT devices at the district inlet (node 1) only. This scenario suggests the adoption of PAT devices in place of a more traditional PRV to control pressure on the distribution network. Scenario 2 simulates the presence of PAT devices in each service connection and not in the district inlet node. Figure 4 shows both the condominium- (Figure 4(a)) and residential- (Figure 4(b)) user systems considering the hypothetical installation of the PAT. Scenario 3 simulates an intermediate condition where PAT devices are installed on each of the five condominium service connections and on the district inlet node. Such a solution was investigated to evaluate the possible benefit of a combination of centralized and decentralized devices.

As mentioned above, PATs were selected according to the average operating condition at the service connections and the district inlet, which were known from the network hydraulic simulation (Scenario 0 – no PAT installed). In the DMA it was possible to identify three different PAT types according to the available head and flow rates. Characteristic curves shift slightly at each time step depending on the PAT rotational speed. Table 1 shows the coefficients of the PAT characteristic curve adopted in the present study and the average percentage error introduced by approximating the PAT characteristic curve using Equation (4).

Values of parameters a and b can be considered constant while c values may change depending on the PAT rotational speed. Values included in Table 1 have to be considered as averages over the simulation period. In the analysis, the M-C type PAT was selected for the main pipe (district inlet), M-B type for condominium users and M-S type for the remainder.

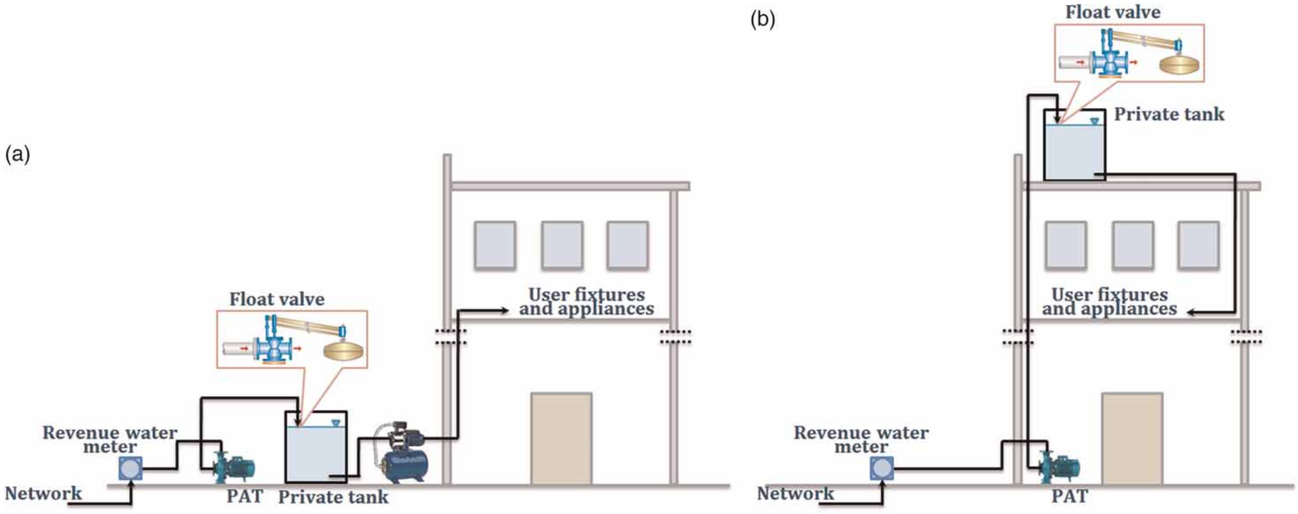

Figure 4 | A schematic of the modelled system considering the PAT installation: (a) with an underground tank and (b) with a roof tank.

Table 1 | Coefficients of PAT maximum efficiency characteristic curve and approximation error ε related to the quadratic interpolating function

PAT model	a	b	c	ε [%]
M-C	4,395.80	-143.92	10.10	0.02
M-B	-4×10^6	28,568	0.99	0.76
M-S	-3×10^6	19,502	0.68	1.02

Considering the high variability of user demands in condominiums and single residential users, as explained in the previous paragraphs, the study attempted to evaluate the impact of changing the PAT characteristic curve at a single-user level. This change can be simply effected by regulating the PAT operating parameters instead of those obtained by network average conditions. The study of PAT characteristic curves showed that PAT operational parameters (Table 1) may vary in a range equal to 40% around the maximum efficiency while maintaining PAT efficiency above 30%.

To numerically investigate the change in PAT characteristic curves in Scenarios 2 and 3, Monte Carlo Analysis (MCA) was used. MCA is commonly employed to evaluate the behaviour of a model and of the simulated physical system to changing conditions and, in the present case, to the possible local regulation of a selected PAT. Characteristic curve parameters (Table 1) were randomly changed, according to a uniform distribution, in the proposed 40% range and 100 random PAT configurations were applied to each node in order to investigate the impact of local PAT regulation. The use of the model can thus allow an understanding of which PAT curve regulation can result in the highest energy production. Model simulations are run for each of the 100 random PAT configurations and the produced energy at each node can be computed thus showing the maximum, the minimum and the average obtainable energy production at each node.

ANALYSIS OF RESULTS

For each scenario, Figure 5 shows the obtained results in terms of stored water volume in the private tank, corresponding to three service connections taken as examples (see Figure 1): a condominium with an underground tank (node 4) and two residential users with roof top tanks (nodes 27 and 34). Some nodes (including node 34) demonstrate a general increase or decrease of the stored volume that is due to the combination of variable pressure levels during the monitored period. Over the long term, this is not a persistent behaviour but, realistically, a long-term filling and emptying cycle. In Scenarios 2 and 3, the PAT characteristic curves were obtained considering the maximum efficiency parameters presented in Table 1.

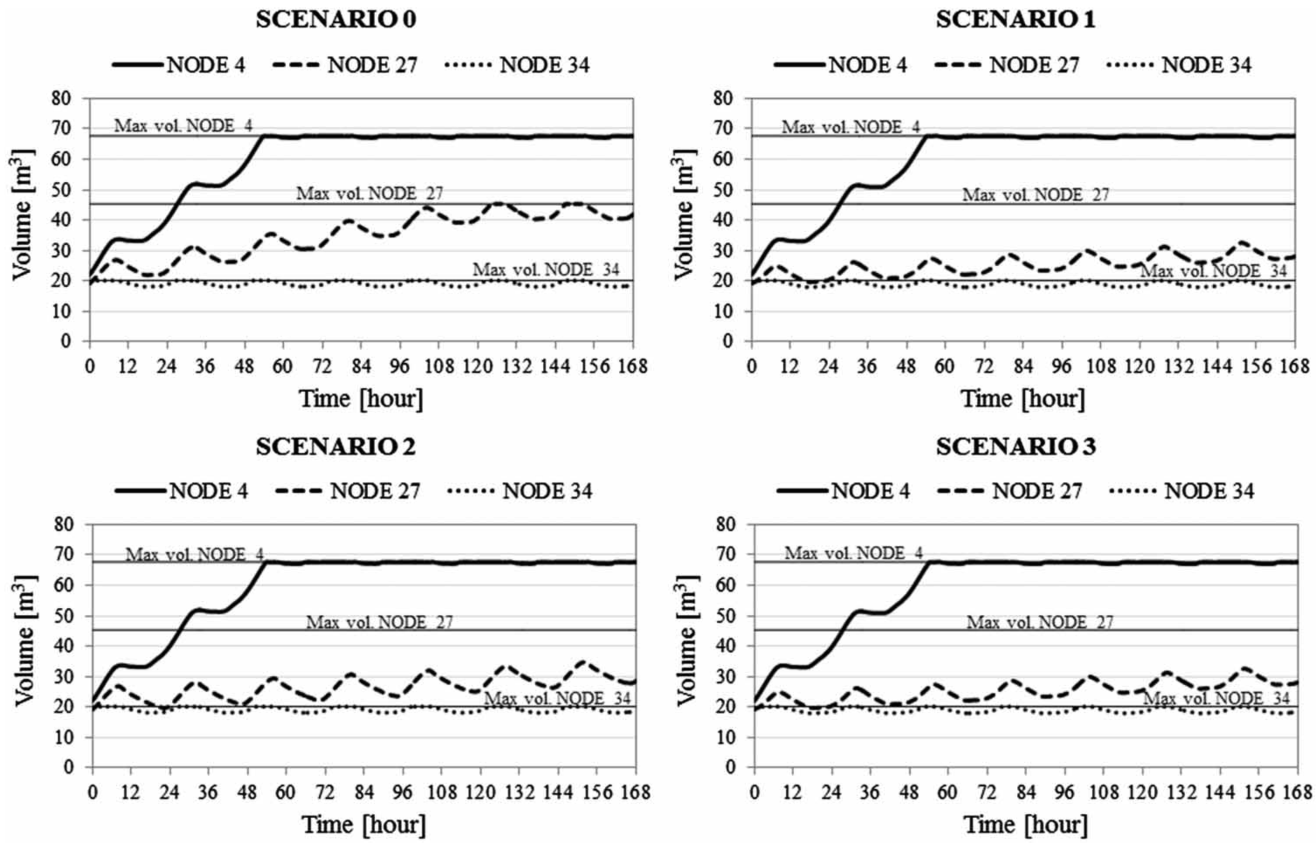

Figure 5 | Stored water volume in the private tanks linked to a condominium with an underground tank (node 4) and two residential users with roof top tanks (nodes 27 and 34).

Analysis of Figure 5 identifies the following considerations:

- The PAT effect in terms of the stored volume is more tangible for node 27, especially when a centralized PAT is simulated at the DMA inlet node (Scenarios 1 and 3).
- The PAT does not reduce the ability of some users to fill their reservoirs, but the filling rate is lower.
- Regarding one of the condominium nodes (node 4): the volumes stored in tanks are quite similar over the scenarios because the pressure available on the tank valve is quite high and even the presence of a local PAT (Scenario 2 and 3) does not reduce flow in a significant way.
- Finally, considering the single user residential node (node 34), the differences between scenarios are not relevant due to the low flows serving the user so the presence of the PAT is shown not to be affecting inflows in a significant fashion.

Figure 6 illustrates the energy production during the day in Scenario 2 at three of the reference nodes. Node 4 is a condominium and the energy production is notably higher because of the higher flow through the service connection; energy

Figure 6 | Energy production from nodes 4, 27 and 34 in Scenario 2 during a 24-hour simulation.

production is at a maximum during the night because the ball valve is totally open; while, during the day, energy production is reduced due to the lower flow and pressure on the service connection. The tank is always supplied by the network and the energy production is continuous. The other two nodes are single users and the energy production is lower and discontinuous during some parts of the day because the tank is totally full and/or the network pressure is too low for supplying the tank. The usability of produced energy is thus greater for the condominiums both for the quantity of supplied power and the continuity of its production.

Figures 7 and 8 show the results of Monte Carlo simulations for the single-user service connections and for condominiums, respectively, under Scenario 2. For all 100 random simulations, energy production was computed offering a statistical interpretation of obtainable energy depending on local regulation of each PAT. The graphs are presented in terms of box and whisker plots in order to show the optimized selection of PAT regulation: the black point showing the maximum average energy production, the average condition and 25th and 75th percentiles regarding PAT regulation. Single users may produce a maximum daily energy output ranging between 1.2 and 7.2 kWh per day, depending on the combination of flows and available pressure at the node (Figure 7). Figure 7 shows the results related to 27 service connections only: the other eight user connections were omitted from the graph owing to their negligible energy production – linked to the low flow rates supplied to these nodes during the day. Condominium users clearly provide higher energy productions between 12 and 108 kWh per day (Figure 8). The analysis of the results show that for many single users, the application of PAT may be not justified by the energy production, being too low to be economically viable, while such application may be more appropriate for condominium users that may offset part of their energy consumption.

Scenario 3, in which condominium PATs were combined with a centralized installation at the network inlet, resulted in a graph similar to Figure 8: net energy production was lower by about 23% depending on the presence of the centralized PAT.

Comparing the three scenarios on an annual basis:

- Scenario 1 was the least energy productive because a large part of available energy was wasted in guaranteeing sufficient pressure to those nodes characterized by low pressure;
- Scenario 2 provides a significant increase in production but the energy produced is often from PATs operating at low efficiency due to low flows supplying the user;

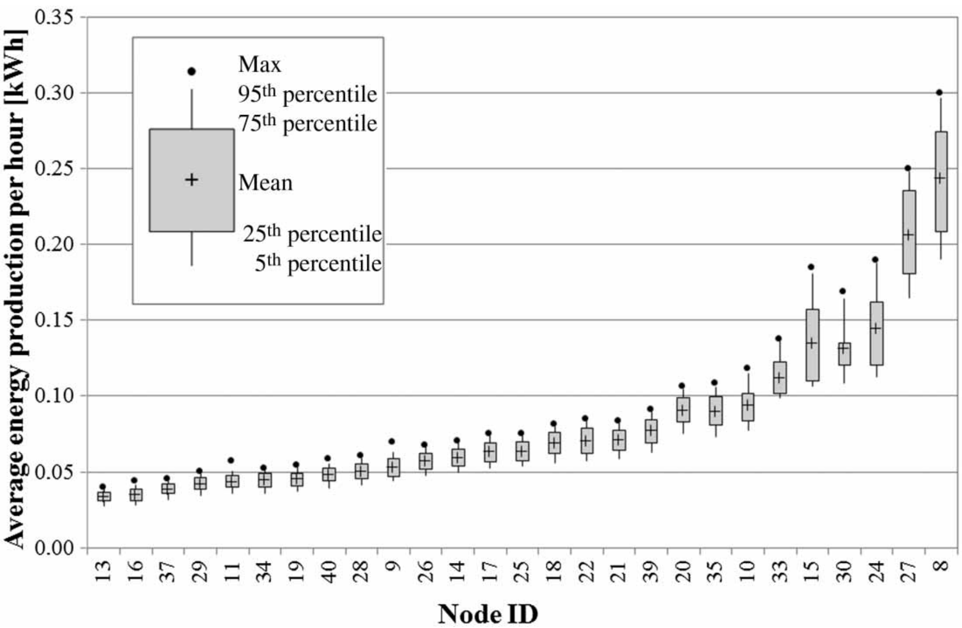

Figure 7 | Average energy production per hour for the single user service connections obtained by performing hydraulic network model simulations with random PAT regulation permutations.

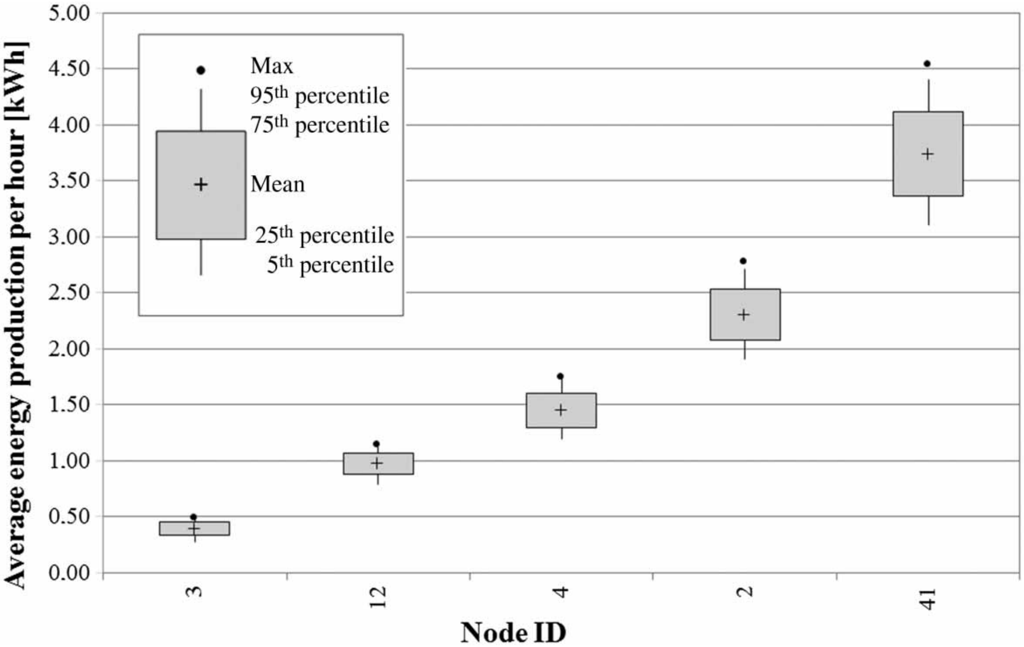

Figure 8 | Average energy production per hour for the five condominium user service connections obtained by running the hydraulic network model with random PAT regulation permutations.

Table 2 | Annual energy production in the proposed scenarios

Average annual energy production [MWh/year]	Scenario 1	Scenario 2	Scenario 3
DMA	60.04	97.53	139.48
For each service connection	1.88	3.05	4.36

- Scenario 3 provides a good compromise thus giving the largest energy production on an annual basis (Table 2). In general, the centralized PAT cut inlet pressures to a level that did not compromise user supply so the average network pressure remains higher than in Scenario 2; the surplus available energy can be then locally used by the decentralized PATs, resulting in a second cut in pressure at the service connection.

CONCLUSIONS

This paper proposes a steady-state hydraulic model able to simulate the effect of PAT devices in WDNs where user supply is a function of pressure. The model takes into account the presence of private tanks by means of the node pressure–consumption law, defining flow emitted from the network and filling the tank, describing the effect of the reservoir and the floating valve on the demand profile. Three different scenarios were analysed involving PATs in order to identify the most suitable solution in terms of energy power production without compromising the hydraulic performance of the network in terms of service delivery.

The analysis demonstrates that the energy production on single residential service connections can be low and also discontinuous – questioning the efficacy of such energy production. Larger, condominium users demonstrate more continuous energy production owing to the fact that the underground tanks remain supplied throughout the day. The choice of a centralized solution with a PAT installed downstream of the DMA inlet node, combined with local PATs on the larger service connections, was thus shown to be the most energy efficient.

Network supply conditions and a possible increase of inlet pressure may change the efficiency of PAT systems thus changing the final choice to another scenario. The results obtained are dependent on the analysed period and on the available data so their generalization cannot be undertaken in a rigorous fashion and further validation should be provided by additional monitoring.

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