Optimal energy recovery by means of pumps as turbines (PATs) for improved WDS management

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ABSTRACT

In water networks characterized by a significant variation in ground elevations the necessity of pumping water in some areas is complicated by a conflicting requirement to reduce excess pressures in other areas. This and the increasing cost of electricity has led to the use of Pumps-operating-As-Turbines (PATs) devices that can reduce pressure (and leakage) whilst harvesting energy. This paper presents a methodology for optimal water distribution system (WDS) management, driving the optimization by minimizing the surplus pressure at network nodes and the operational pumping costs and maximizing the income generated through energy recovery. The method is based on a highly parallelized Evolutionary Algorithm, employing an hydraulic solver to evaluate hydraulic constraints. Water demands at network nodes are considered as uncertain variables modelled by using a probabilistic approach in order to take into account unknown future demands. The approach is demonstrated in different case studies. Results obtained highlight that the economic benefits of installing PATs for energy recovery in conjunction with a combined pump-scheduling and pressure management regime is especially related to the input network characteristics. Further analysis of the importance of the probabilistic approach and of the influence of the interval time step adopted for the optimization has been evaluated.

Key words | energy production, pressure reducing valve (PRV), Pump As Turbine (PAT), water distribution system management

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INTRODUCTION

The conflicting requirements of reducing excess network pressure whilst maintaining acceptable levels of network performance have given rise to the increasing importance of pressure management optimization (e.g. Germanopoulos & Jowitt 1989; Araujo *et al.* 2006; AbdelMeguid & Ulanicki 2011). This is of evidence especially when the terrain of the network is complex, i.e. zones at different elevations coexist and pumping stations are required. In these cases the operational costs need to be minimized by reducing the energy consumption (e.g. Lansey & Awumah 1994; Ramos *et al.* 2012) taking into account the variability of the electricity tariffs during the day (e.g. Giacomello *et al.* 2012; Morley *et al.* 2013). Furthermore, increasing energy costs have guided some approaches (e.g. Artina *et al.* 2008; Fontana *et al.* 2012; Carravetta *et al.* 2013a; Giugni *et al.* 2014; Tricarico *et al.* 2014a, b; Jafari *et al.* 2015; Parra & Krause 2017) towards using the pressure dissipation as a mechanism for energy production by inserting turbines or pumps operating in reverse which can act as turbines (Pumps As Turbines – PATs) (Agarwal 2012), even where private tanks have been

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installed (e.g. De Marchis et al. 2014, 2016; Puleo et al. 2014). However, the use of PATs is nowadays limited mainly by the difficulty of predicting the efficiency of a pump operating in this fashion. This information is not yet disseminated by the device manufacturers and this has led to several studies that tackle this issue based on experimental data or through computational fluid dynamics analysis in order to estimate the PAT performance (e.g. Williams 1995; Derakhshan & Nourbakhsh 2008; Nautiyal et al. 2010; Fecarotta et al. 2011; Carravetta et al. 2012, 2017; Pugliese et al. 2016; Lydon et al. 2017). Nevertheless, these investigations do not cover the entire speed range which could be of interest and thus are limiting the applications of PATs in real systems. Naturally, if a PAT is installed where a reduction of pressures was already considered necessary, in order to use that head for energy production, it is required to establish the limitations of PAT mode operation – at the same time guaranteeing the pressure reduction required in the network for appropriate operation. Several approaches are thus used to determine the optimal device for the specific case study location and its effectiveness (e.g. García et al. 2010; Carravetta et al. 2013b, 2014; Rossi et al. 2016).

In a water distribution system (WDS) management problem some authors (e.g. Giustolisi et al. 2013; Morley et al. 2013) have nevertheless highlighted the importance of taking into consideration both the aspects of reducing pumping costs and reducing leakage, i.e. through limiting pressure within the network simultaneously in the optimization process in order to detect the optimal Pareto Front. On this basis, a multi-objective optimization approach which reduces the energy consumption in a WDS by minimizing the pumping costs taking into account the variability of the electricity tariffs during the day and considering both the placement of the PATs and the equivalent pressure setting necessary to minimize leakage within the network and to maximize the economic benefit derived from energy recovery is herein applied to different case studies. Moreover, in order to accommodate for the uncertain future, the robustness of the solutions is optimized by assuming uncertain future water demands characterized using appropriate distribution functions (Tricarico et al. 2007; Gargano et al. 2016, 2017). This, in turn, has been integrated into the optimization process to enable identification of a more robust set of final solutions.

The main aim of this study is to make a first contribution in the investigation of the efficiency in using PATs as a strategy for energy cost reduction as a function of the different topological characteristics of the networks whilst simultaneously considering optimal WDS cost-pressure management analysis. In particular the effect of the topological scheme and the terrain on PAT income is demonstrated. Furthermore, the results section analyses in detail the effect of the main hydraulic input parameters on maximum PAT revenue estimation and the influence of the interval time scale on maximum PAT income generation. The results obtained highlight that the economic benefits of installing PATs for energy recovery in conjunction with a combined pump-scheduling and pressure management regime are particularly related to the network input characteristics. Furthermore a probabilistic approach in considering the water demand leads to a more robust configuration.

METHODOLOGY

The proposed study is based on a multiobjective problem which considers as objectives the minimization of surplus pressures coupled with the minimization of the pumping costs while at the same time maximizing PAT income. The last two cost objectives have been kept by intention separate for underlining the difference in between the revenue respect to the operative costs of pumps. Nevertheless an insignificant change is observed if the problem's complexity is reduced by considering the last two objectives as a single objective (Tricarico et al. 2014b). The three-objective problem has thus been formulated by considering:

$$\text{Minimize:APC} = \sum_{t=1}^{T}\sum_{k=1}^{N_p} P_k^t c^t \tag{1}$$

$$\text{Minimize:SP} = \sum_{t=1}^{T}\sum_{i=1}^{n} (P_{i,t} - P_{\min}) \tag{2}$$

$$\text{Maximize:API} = E \cdot e - M_{\text{PAT}} \tag{3}$$

where: APC is the annual pumping cost; T is the number of time steps in the extended period simulation; N_p is the number of pumps in the network; P_k is the power consumption of the k-th pump at time step t [kw/h]; c is the energy cost tariff for the k-th pump at time step t [€/kw/h]; SP is the surplus pressures; $P_{i,t}$ is the pressure calculated at node i in the interval time t; $P_{\min}$ is the minimum pressure requirements for fully satisfying the water demand; API is the Annual PAT Income; E is the annual PAT energy (see Equation (12)); e is the energy price; M_{PAT} is the annual PAT cost (sum of the annual maintenance cost, amortized turbine and installation cost).

The optimization is thus subject to the hydraulic equation constraints, for each time step:

$$\sum_{j=1}^{N_l} A_{ij}Q_j - Q_{DEL_i} = 0 \quad (i = 1, \ldots, N_n) \tag{4}$$

$$\sum_{i}^{N_n} A_{ij}H_i = H_{j,1} - H_{j,2} = r_j \cdot q_j \cdot |q_j|^{\varepsilon-1} \quad (j = 1, \ldots, N_l) \tag{5}$$

where: A_{ij} are coefficients of the incidence matrix (a 0, +1 or −1); Q_j is the flow in the j-th pipe; Q_{DEL_i} is the delivered flow at the i-th junction node; N_n is the number of junction nodes (for the mass balance); $H_{j,1}$ is the head at the upstream node of the j-th pipe; $H_{j,2}$ is the head at the downstream node of the j-th pipe; r_j is the coefficient of the j-th pipe (headloss formula, function of pipe length, diameter and roughness coefficient); ε is the flow exponent function of the headloss formula used; N_l is the number of network links.

The hydraulic feasibility of the solution has been checked by considering that water demand at nodes should be fully satisfied and pressures at any node should be equal to or greater than a minimum pressure.

As a further constraint requirement, levels of any tanks/reservoirs in the system at the final time step should be at least as high as they were at the beginning of the scheduling horizon, in order to produce a sustainable system operation.

$$P_i^t \geq P_{\min} \ if \ Q_{DEL_i}^t > 0 \quad i = 1, \ldots, N_n \ ; \ t = 1, \ldots, T \tag{6}$$

$$(L_{i,0} - L_{i,T}) \geq 0 \quad i = 1, \ldots, N_s \tag{7}$$

where: N_s is the number of network tanks; P_i is the pressure at the i-th network node; $L_{i,0}$ is the level of the i-th tank at the initial time step; $L_{i,T}$ is the level of the i-th tank at the final time step.

For the purposes of pump scheduling, pump decision variables are defined as the unknown status of each pump (1 – working, 0 – not working) for each hour of the scheduling horizon (smaller time intervals can be used too, if appropriate). In addition, prior to the optimization, each pump may have its status fixed to 'Always on', 'Always off' or to respect the existing pump control as defined in the hydraulic model – i.e. to exclude it from the optimization process altogether.

The selection of PATs can either be done globally, in which any PAT defined in the EPANET model (Rossmann 2000) can be installed with any of the PAT types defined, or a restricted subset of the PATs can be replaced up to a user-specified quantity. In addition, the initial water levels of each of the tanks in the system can be considered as decision variables.

The above problem has been constrained by considering all of the possible PAT allocations in the network by considering different PAT curves which could be chosen as a function of the flow and pressures available at the point of installation. A wide set of PAT characteristic curves have been considered by varying the number of stages and impeller diameters in order to cover almost all the entire range of flow-pressures that might be encountered. In particular, for this case study, 33 different pumps of the KSB brand (www.ksb.com) have been modelled which could be employed as PATs in reverse mode. The rotational speed of the pump has been considered nominally as 1,450 rpm while operating in turbine mode, and the rotational speed has been considered as 1,500 rpm.

The Best Efficiency Point (BEP) has been calculated according to the formulation of Williams (1995), in which is possible to determine Q_{tb} and H_{tb} of the PAT from the BEP of the pump:

$$Q_{tb} = \frac{N_t}{N_p} \cdot \frac{Q_{pb}}{\eta_{pb}^{0.8}} \quad H_{tb} = \left(\frac{N_t}{N_p}\right)^2 \cdot \frac{H_{pb}}{\eta_{pb}^{1.2}} \tag{8}$$

where: Q is the flow rate; H is the head; N is the rotational speed; η is the efficiency; and the subscripts p, t and b refer to pump, PAT, and BEP, respectively. According to the experimentation undertaken by Derakhshan & Nourbakhsh (2008), the BEP of the PAT was supposed to coincide with pump BEP.

The PAT power (kW) at its BEP can consequently be calculated by:

$$P_{tb} = \rho g Q_{tb} H_{tb} \eta_{tb} \tag{9}$$

where: ρ and g are the fluid density and gravitational acceleration respectively.

Because water demand varies in a water distribution network, it is necessary also to study the characteristic curves away from the BEP. The estimation of the PAT characteristic curves on the basis of the BEP has been done with reference to the same experimental study described above (Derakhshan & Nourbakhsh 2008), which is valid for a pump rotational speed of 1,450 rpm, a PAT $N_t = 1{,}550$ rpm and for centrifugal pumps with specific speed $N_s < 60$ (m, m^3/s):

$$\frac{H_t}{H_{tb}} = 1.0283\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.5468\left(\frac{Q_t}{Q_{tb}}\right) + 0.5314 \tag{10}$$

$$\frac{P_t}{P_{tb}} = -0.3092\left(\frac{Q_t}{Q_{tb}}\right)^3 + 2.1472\left(\frac{Q_t}{Q_{tb}}\right)^2 - 0.8865\left(\frac{Q_t}{Q_{tb}}\right) + 0.0452 \tag{11}$$

The PAT power, P_t, can be calculated for each time interval in which the day has been segregated and for each PAT. The product of it for the time interval (Δt) in which the PAT is working in a year is the energy (kWh):

$$E = \sum_{PAT=1}^{NPAT} \sum_{t=1}^{24} \rho\, g\, Q_t\, H_t \eta_t \Delta t \tag{12}$$

The PAT annual revenue can thus be estimated by multiplying the result of Equation (12) by the tariff of energy purchase. The cost of energy selling varies as a function of the total power (MWh) produced. For example, according to Italian financial law, an energy price of 220 €/MWh could be considered for power generation lower than 1 MW.

The annual PAT income that needs to be maximized in the optimization problem is thus obtained by subtracting the PAT cost (annual maintenance cost and amortized turbine and installation cost) from the annual revenue. As a preliminary study, maintenance cost can be considered to be 15% of the total turbine installation costs, a function of the PAT installation costs and of the civil works required for its installation, which could be approximated as being 30% of the PAT installation costs (Fontana et al. 2012). The latter can be estimated on the basis of the installed power as being of the order of 545 €/kW, considering the sum of the costs of the PAT, the generator and the inverter required to connect the installation to the electrical distribution network (Carravetta et al. 2013a). The ratio between the total installation costs and the annual income determines the number of years before a return on investment can be expected.

The optimization employs the multi-objective Omni-Optimizer algorithm (Deb & Tiwari 2008). This algorithm belongs to the Genetic Algorithm (GA) family of population-based evolutionary algorithms and has been successfully employed in a number of WDS optimization applications (e.g. Vamvakeridou-Lyroudia et al. 2009; Morley et al. 2012) and is well suited to applications involving both discrete integer and real decision variables. This algorithm has been augmented with the robust optimization technique introduced by Kapelan et al. (2006). This approach employs a concept of nested, in-process sampling that allows greater confidence in the range of objective values when considering uncertain parameters – in this case, system demand.

CASE STUDIES

The methodology above reported has been applied to four different case studies characterized by different topological characteristics, dimension and populations: (1) the Net1 network derived from EPANET examples (Rossmann 2000) in which the measurement unit has been changed to the International System and a residential demand pattern has been introduced to the original formulation; (2) a revised version of the Anytown network, herein called the AT network (Walski et al. 1987), in which in particular the three pumps have been considered working at the higher performance; (3) the D-Town network (Marchi *et al.* 2014); and (4) the trunk mains model of the Sorrento Peninsula, Italy, located in the Campania region, between the Gulfs of Napoli and Salerno (Tricarico *et al.* 2014a, 2014b).

In Figure 1 and Table 1 topological characteristics of the four systems are reported.

For each scheme examined, the minimum pressure requirement has been set equal to 10 m for all nodes with an associated demand and the extended period simulation has been considered of a single day with interval times of 1 hour, with the only exception being the D-Town case study in which, so as not to alter the original scheme, the number of interval times has been kept as it was equal to 168 with a time step of 15 minutes. For each interval time the flow has been considered as a random variable and has been modelled by means of the normal distribution in which the mean value is the base demand at network nodes and the CV is set equal to 0.1, it being considered that the case studies are of large

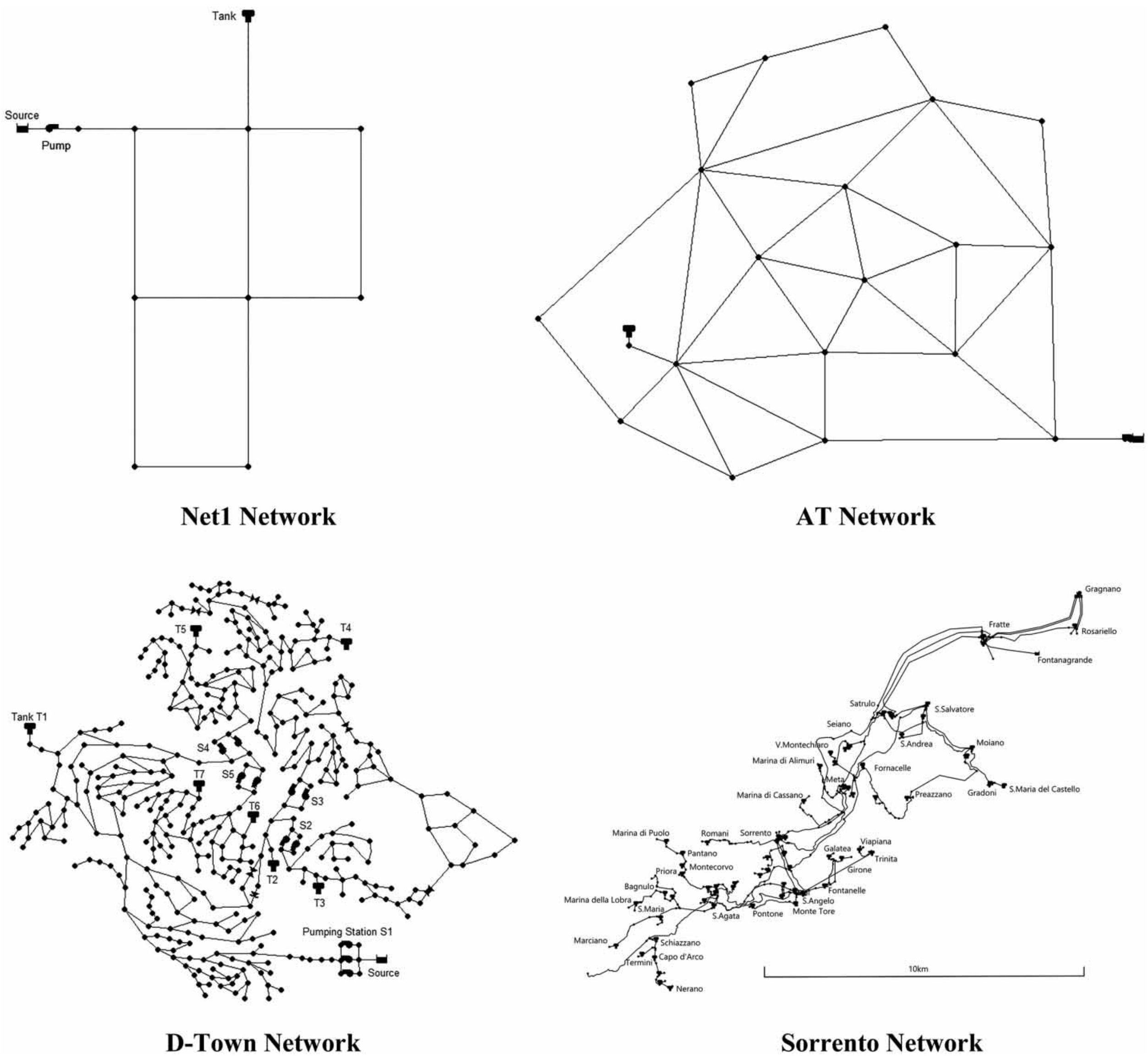

Figure 1 | Topological schemes of the examined networks.

Table 1 | Topological characteristics of the examined networks

	Net1	AT	D-Town	Sorrento
Elevation range [m]	210.312–216.41	6.1–36.6	3.5–105.6	0–675
No. reservoirs	1	1	1	2
No. tanks	1	1	7	68
No. pumps	1	4	11	13
Total pipe length [m]	19,364	98,473	116,864	142,170
Pipe diameters range [mm]	152.4–457.2	101.6–304.8	51–610	60–1,000

networks which supply a number of users greater than 1,000 (Tricarico *et al.* 2007). If negative values of water demand were generated from the distribution, a zero value for demand has been considered. In order to constrain the search space, the total number of PATs to be installed has been limited to a maximum of ten, this being the threshold value determined for the Sorrento case study in order to maximize the power generation income (Tricarico *et al.* 2014a). For each PAT, there is the possibility to choose among the 33 available PAT characteristic curves, and in addition, an 'install nothing' option is available.

The minimization of the surplus pressure (Equation (2)) and the pumping costs (Equation (1)), coupled with the maximization of PATs income (Equation (3)) leads to a Pareto Front of solutions which takes into consideration all these objectives collectively. Several simulations, varying the random seed, i.e. the initial population, have been undertaken for each of the four case studies examined and selected Pareto Front solutions respectively for the Net1, AT, D-Town and Sorrento networks are shown in Figure 2.

Each single solution (i.e. point) of the Pareto Front thus corresponds to a different network configuration where it could be different: (1) the number of pumps on/off and in which time step of the simulation they are active; (2) tank levels; (3) where PATs are allocated from all the possibilities and which type of turbine with relative characteristic curve is applied.

In Table 2, the solutions found with the maximum PAT income and the corresponding API and SP are reported for the different case studies examined.

As an example, in Figure 3, for the complex case study of the Sorrento network, we report the allocation of the ten PATs for the solution obtained in the Pareto Front with the maximum PAT income generated (Table 2). Different points of the Pareto Front correspond to different network configurations and thus PAT allocations could be chosen from 102 possible allocations for this specific case study. Of course, for each of them, one of the 33 possible turbine characteristic curves previously inserted in the inputs is then selected.

Analysis of the results and plots provides evidence that the PAT income in the AT network does not correspond to an evident reduction of the operational costs, while the D-Town network shows a benefit of about 15%. Net1 is instead highlighting an increase in the percentage of recovery with APC almost totally covered by the API (97%), while the Sorrento water system is characterized by a significant benefit in energy production (greater than 100% for many of the solutions).

These results are a function of the different characteristics of the four case studies examined and in particular of the topology and terrain of the systems. In order to analyse the influence of these latter on the results of the proposed methodology, an index (I_{Net}) is here considered which is a performance indicator of the main network characteristics:

$$I_{Net} = \frac{H_{\text{Tank, max}} - Z_{\text{Min}}}{L_{\text{Tot, Net}}/N_{\text{Tanks}}} \tag{13}$$

where: $H_{\text{Tank,max}}$ is the maximum level of the tanks in the network; Z_{min} is the minimum elevation; $L_{\text{Tot,Net}}$ is the total length of the network; N_{Tanks} is the number of tanks present in the system.

Table 2 reports the above described index too and the corresponding percentage of recovery obtained by inserting PATs in the system.

As it is expected, by increasing the available head in the network, i.e. increasing the I_{Net} index, the income from the application of PATs in the system increases. On the other hand, when the terrain of the system is not greatly variable and the network is highly looped, the income from energy production by PATs application needs to be evaluated accurately. By means of further analyses on different case

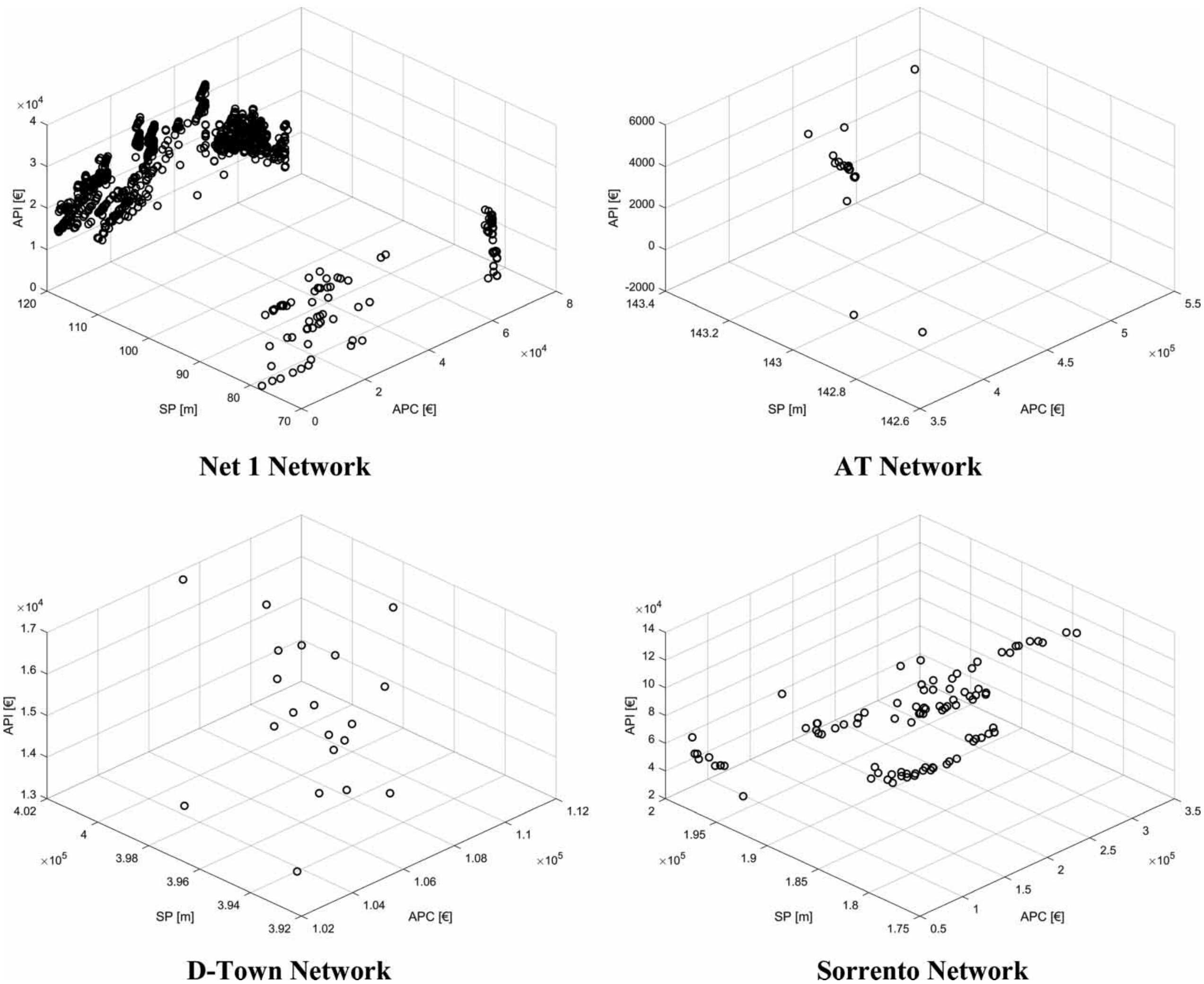

Figure 2 | Selected Pareto Front solutions for the four networks examined.

Table 2 | I_{Net} and mean PAT income values for the networks considered

	I_{Net}	APC [€]	SP [m]	API [€]	% Recovery
Net1	4.90E-03	41,336.1	113.988	40,013.4	97
AT	7.10E-04	401,120	143.032	5,142.56	1
D-Town	8.00E-03	107,857	399,234	16,793.4	15
Sorrento	3.50E-01	73,961	190,537	120,947	163

studies, it would be helpful to detect a limit of applicability of this methodology as a function of the input network characteristics.

As a further result, the importance should be highlighted of assuming the water demand to be an uncertain parameter in the water management analysis leading to solutions which dominate the deterministic ones. As already highlighted in Tricarico et al. (2014a) in reference to the Sorrento case study, a probabilistic approach was found to lead to more robust solutions with different network configurations, compared with the deterministic approach. This result has been analysed further with reference to the Net1 example, below. Additionally, the time interval in which the water demand has been segregated affects the results of the optimization. Indeed, the lower the time interval in which the water demand is averaged, the more accurate the water demand estimation.

With the sole aim of making an example, Net1 has been further analysed by considering the water demand averaged

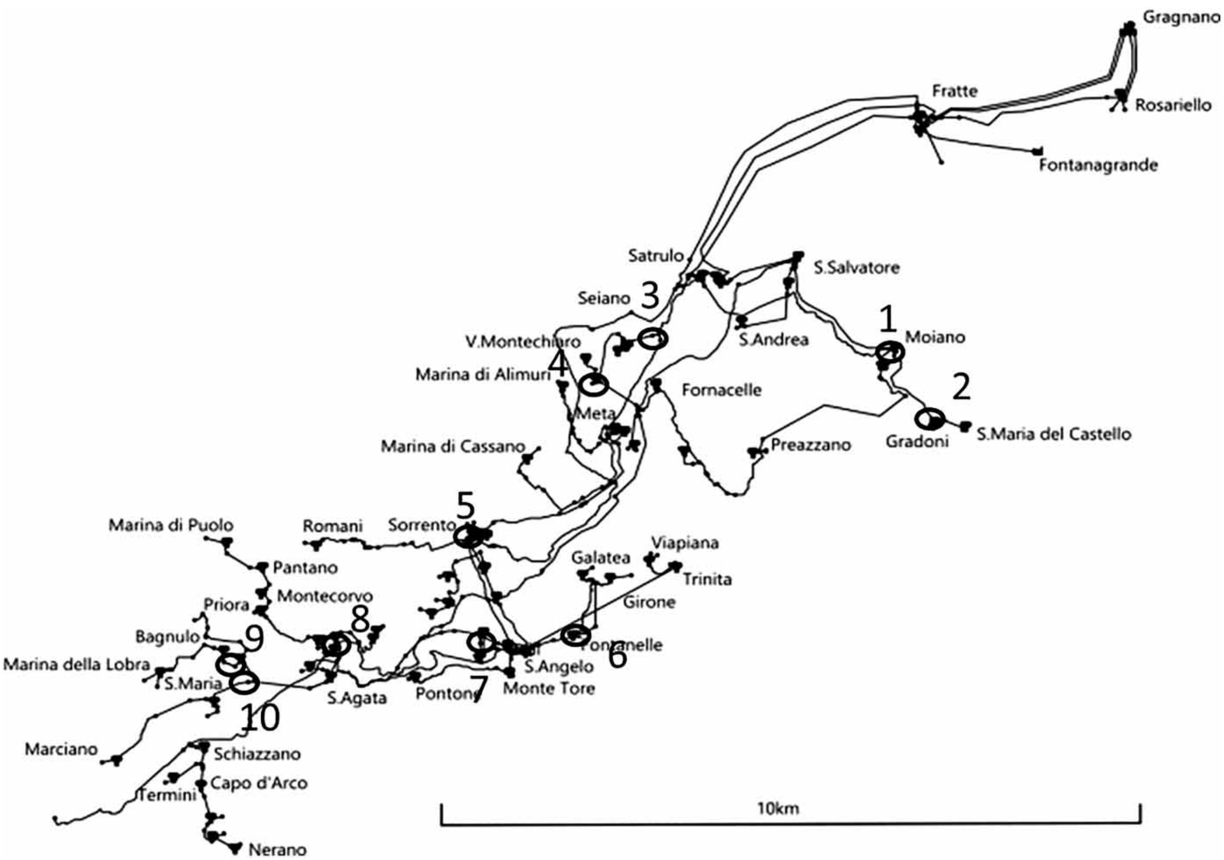

Figure 3 | PAT allocation for the maximum PAT income generated solution for Sorrento.

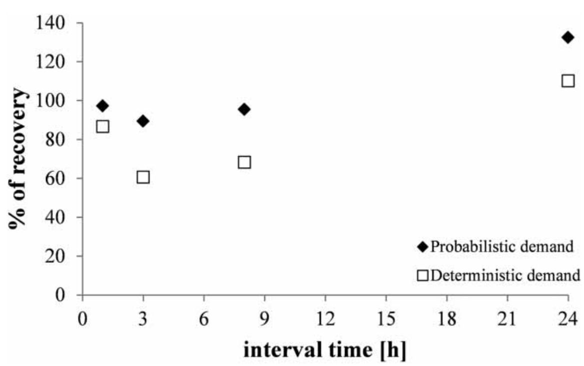

Figure 4 | Interval time discretization analysis with the deterministic and probabilistic approaches for Net1.

not only on the interval time of 1 hour so far considered, but also with greater time intervals: 3 h, 8 h, until keeping it constant for the whole day (24 h). The same analysis has been done considering thus the variability in water demand by means of the probabilistic approach and in comparison by considering it deterministically. As we can see from the plot shown in Figure 4, considering the probabilistic approach leads to a more accurate estimation of the percentage of recovery. Furthermore results are different as a function of the different time intervals considered.

CONCLUSION

The principal aim of this work has been to develop a methodology for the optimal management of a water system by considering the reduction of annual pumping costs by means of the selection of the location and operation of PATs in a water distribution system. The proposed approach is effective when the hydraulic system considered presents redundancy. The optimization is driven by the minimization of leakage (via minimization of surplus pressure at network nodes), the minimization of operational pumping costs and the maximization of the income generated through energy recovery. Decision variables are locations and types of PATs to be installed and the related pump schedules and initial tank levels. The optimization was performed by using evolutionary algorithms and by considering a probabilistic approach to water demand assessment. The methodology was tested on different case studies.

The results obtained demonstrate that installing PATs along water mains for energy recovery has a different economic benefit in conjunction with a pump-scheduling and pressure management regime. The derived revenue is a function of the input characteristic of the water system considered. In particular, networks characterized by a high difference in pressure level have a greater income from PAT energy production while this comes at a cost of considering highly looped networks with no surplus pressure, i.e., reduced ability to respond to various system failures such as pipe bursts (AT network). Furthermore, the probabilistic choice adopted in this analysis has led to more robust solutions with respect to a deterministic approach and thus considering a shorter time interval for water demand segregation.

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